AGRICULTURAL POTENTIAL OF FORESTED LAVA LANDS (TROPOFOLISTS)

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INTRODUCTION

Tropofolists are thin forested organic soils which cover lava lands on the island of Hawaii and parts of the slope of Mount Haleakala on the island of Maui. Eleven percent of the State of Hawaii or 0.47 million acres are in soils classified as Tropofolists. This area, equal to 1.2 times the extent of the island of Oahu, constitutes the State's largest single undeveloped soil resource. A small fraction of this land is currently used for urban, recreational and agricultural purposes. The remaining area is still largely in native forest.

Four diversified agricultural crops, macadamia, papaya, coffee and floriculture are cultivated on these soils. These soils are also used for ranching. At the Malama-Ki and Waiakea Research Stations of the Hawaii Agricultural Experiment Station, other fruit, vegetable, forage and ornamental crops have been successfully grown on this soil.

Future development of this land for agricultural and nonagricultural purposes appears inevitable. In this report, existing information and new data have been compiled to enable government planners and private owners to judge the potential of this little known and extensive resource. With this goal in mind this study focused on three major objectives. They were:

1. To determine the role of organic matter in the retention of water and plant nutrients in aa land under different climatic conditions.

2. To determine the fate of organic matter after clearance of forest lands for cultivation.
3. To determine the extent of forest soils and to identify criteria for land use.

STATE OF KNOWLEDGE

Soil Studies

A taxonomic key to the Tropofolists can be found in the first draft of the Soil Taxonomy (USDA Staff, 1972). The Tropofolists were, for the most part, included in the Soil Taxonomy to accommodate the forested lava lands of Hawaii.

In the Great Group Classification of the soils of the Territory of Hawaii (Cline et al., 1955), Tropofolists were placed in the Lithosols great soil group. All soils in this group were mapped as land types. The Tropofolists, as we presently know them, were categorized as Rockland types with volcanic ash. The land types within this category were further differentiated on the basis of the overlying volcanic ash which in turn were named after climatic zones and still further according to the character of the underlying rock.

The terms Lithosol and Rockland connote land or soil with low agricultural potential, and these names may have had some influence in keeping the land from earlier development. There is a danger that reclassification of these soils as Histosols (organic soils) will have an opposite effect.

The reclassification of Lithosols into Histosols resulted in a study of organic soils of the State by Yaibuathes (1971). She examined and characterized the Tropofolists and Troposaprists, placing greater emphasis on the former. Troposaprists are organic soils of highly decomposed organic materials that occur in the tropics. In Hawaii, they are generally found on the summit and forested areas of the older islands. Mt. Kaala on Oahu and Mt. Waialeale of Kauai are examples of two areas where this soil occurs. The present report does not include a study of Troposaprists.

Yaibuathes' work was mainly concerned with a study of the organic layer (histic epipedon). The current study combines Yaibuathes' findings with additional data on the lava substrata so that the value of the soil for crop production can be made.

The need for soil classification arises from the fact that the forested lava lands or the Tropofolists have varying degrees of potential for development. A soil properly characterized and classified should give the user a good indication of its potential use. This indication of potential use may come from research such as that carried out on the Malama-Ki and Waiakea Research Stations located on this type of soil or from the experience gained by users of similar soils.

The flow chart in Figure 1 illustrates an example of the classification of a soil. The Papai series, for example, is a member of the euic isohyperthermic family of Typic Tropofolists. The bulk of the papaya industry in Hawaii is currently grown on this soil. There are 21,000 acres of this soil series in the State, all of them on the island of Hawaii.

In Figure 1 we see that all soils can be separated on the basis of whether they consist of inorganic or organic materials. Organic soils are called Histosols at the highest category of classification. There are nine orders of inorganic soils.

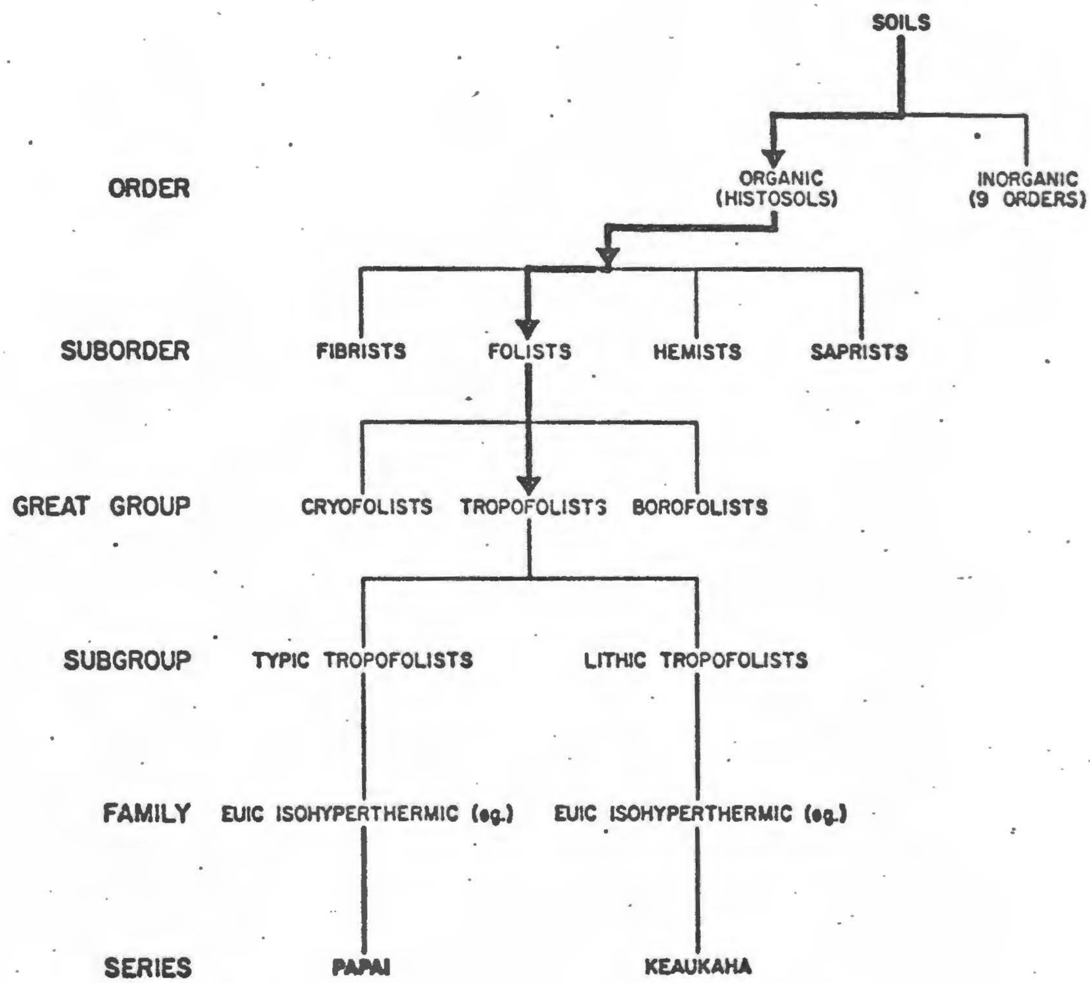

Figure 1. Classification of organic soils with two examples classified to the soil series level.

Histosols are subdivided into suborder categories on the bases of the moisture regime and degree of decomposition of the organic debris. The Folists are exceptions and they are Histosols that:

1. are never saturated with water for more than a few days following heavy rains and have
   a. a lithic or paralithic contact less than 1 m from the surface, or fragmental materials with interstices filled or partially filled with organic materials in half or more of each pedon, or both, and
   b. less than three-fourths of the thickness of organic materials as Sphagnum (spp), fibers, and
2. have no mineral layer more than 10 cm thick above a lithic or paralithic contact and the organic materials are more than twice the thickness of the mineral layer.
3. have 20 percent or more organic carbon.

The Folists are in turn subdivided at the great group level into Borofolists, Cryofolists and Tropofolists. Tropofolists are the Folists which occur in the tropics. The forested lava lands of the island of Hawaii are the prime example of Tropofolists.

By definition, Tropofolists have very thin organic layers. In fact this layer must be thinner than one meter. In Hawaii, the organic layer is generally from two to eight inches thick.

There are two subgroups of Tropofolists. The subgroup occurring on aa lava is classified as Typic Tropofolists while that occurring on pahoehoe lava flows is called Lithic Tropofolists. The separation of Tropofolists on the basis of the texture of the underlying lava is very useful. The agricultural potential of Tropofolists is largely determined at this level of classification and is the main reason for the difference in the values of the Papai and Keaukaha series (see Figure 1).

Lithic and Typic Tropofolists are further subdivided at the family level on the bases of the pH of the organic layer and soil temperature. If the pH is less than 4.5 the soil is placed in the dysic (infertile) family and in the euic (rich) family, if the pH is greater than 4.5.

The air temperatures and therefore, soil temperatures of the tropics do not vary greatly between summer and winter. They can, however, vary considerably with elevation. Tropofolists which occur below 1000 feet elevation are placed in the isohyperthermic families. The iso prefix indicates less than 5° C (9° F) degrees difference in soil temperature between mean summer and winter temperatures, and the term hyperthermic indicates that mean soil temperature is greater than 22° C (72° F). The isothermic families are soils which occur between 1000 to 3500 feet elevation and have soil temperatures which are between 15° C (59° F) and 22° C (72° F). Soils in the isomesic families occur at elevations from 3500 to 7000 feet and have soil temperatures between 8° C (47° F) and 15° C (59° F). The grouping of soils on the basis of temperature is also important. The use of high elevation soils for crop production is largely restricted by low temperatures.

Lastly, Tropofolists which are identically classified at the family level are separated into soil series on the basis of rainfall.

At this category, the name of the area where the soil was first described is used.

Figure 2 provides the basis for classification of all 14 series within the Tropofolist great group in Hawaii.

The soil conservation service of the United States Department of Agriculture has completed a reconnaissance survey of Tropofolists for the Island of Hawaii. A reconnaissance soil survey is usually designed to explore and delineate areas of soils suitable for more intensive development.

The soil survey maps can be found in the appendix of this report.

Crop and Soil Management

Until the establishment of the Malama-Ki and Waiakea Research Stations on forested lava lands some 10 years ago, there were few published reports on crop and soil management on Tropofolists. Powers _et al._ (1932) published a bulletin which contains a survey of the physical features that affect the agriculture of the Kona district. This report contains a map which includes information on rainfall, elevation and coffee production as well as geology. They divided the soils in the study area into six classes: pure ash, scoriaceous ash, pockety ash, ashy scoria, scoria and flow rock. Powers, a professional geologist, expressed amazement at the agriculture on lava land.

> "It is a remarkable sight to see a planter clearing off a field of this bare black lava and planting his coffee trees in cracks or in holes which he has blasted, and then later to note the thrifty

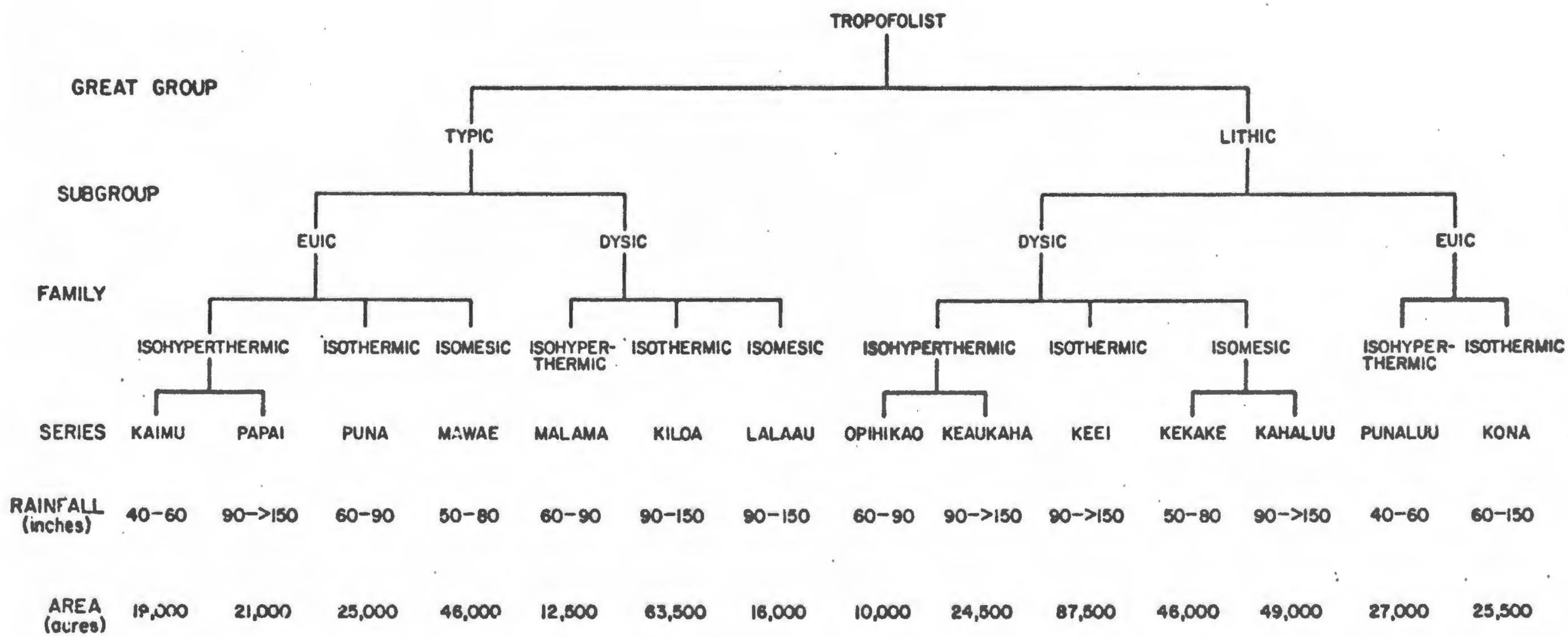

Figure 2. Classification of Tropofolists.

> growth of the trees. The property of these flows most difficult to understand is that being able to supply the plant with water even during protracted dry spells. Their extreme permeability, due to profuse jointing, causes them to take in large part of the total rain which falls. Their ability to supply moisture for plant growth is probably based on the gradual penetration of water along the fine cracks and vesicles within the rock."

Ripperton *et al.* (1935) elaborates on the influence of rainfall and elevation on coffee production in Kona. They designated the zone from sea level to 800 feet elevation which receives 25-40 inch rainfall as the semiarid belt. The region from 800 to 2200 feet elevation was designated as the lower humid zone and has a rainfall range between 40 - 80 inches. The rain belt lies between 2000 and 2800 feet and was considered by Ripperton *et al.* to render agriculture impossible because of limited sunshine and heavy rain. A region of decreasing rainfall designated as the upper humid zone, occurs just above the rain belt.

Most of the coffee was and still is grown in the lower humid zone where rainfall is adequate and temperature and sunlight are still sufficient for high coffee production. Within this zone, land use for crop production is high in areas covered with deep volcanic ash, moderate on forested aa land and low on forested pahoehoe land and recent lava flows. Powers *et al.* (1932) noted coffee plantings on bare pahoehoe devoid of ash or humus accumulations. They also noted that coffee grew well on pahoehoe in its early stages, but that dieback was more common on pahoehoe land than on ash soils.

There are other published reports on the mineral nutrition of coffee (Beaumont and Fukunaga, 1958; Cooil *et al.*, 1961; Sherman et al., 1961) but no mention was made of the special management requirements of forested lava soils.

In 1949, a major planting of macadamia was started in Keaau, Hawaii, on forested lava land. Clearing of an additional 1000 acres was started in 1972 on an adjacent site of the same soil series. By 1966, Cooil et al. had published a report on phosphorus nutrition of macadamia based on experiments conducted at Keaau.

The largest single planting of macadamia nut on forested lava soil is in Honomalino, in South Kona. This orchard covers a wide range of soil and climate, and their effect of crop performance is quite apparent.

The experience gained from macadamia nut production in Keaau and Honomalino and from the ongoing research at the Waiakea and Malama-Ki Research Stations now provide a better basis for evaluating the agricultural potential of Tropofolists.

Papaya production in the Puna district of Hawaii began to expand in the early 1950's. Shoji et al. (1958) conducted fertilizer experiments for papaya in Kapoho, Puna. Their results confirm the findings of others that high rates of fertilizers are needed to obtain higher yields of coffee, macadamia and papaya.

A survey of ongoing and completed research on the Malama-Ki and Waiakea Research Stations is summarized in Table 1. This survey provides a picture of the range of crops which can be grown on forested lava lands. It should, however, be noted that not all crops planted on these stations were grown to test the suitability

Table 1. Ongoing or Completed Research at Malama-Ki and Waiakea Research Stations[a]

Crop	Nature of Research	Waiakea	Malama-Ki
Acerola	Culture		+[b]
Anthurium	Breeding	+[b]	
Avocado	Variety selection		+
Banana	Culture	+	
Citrus	Nutrition experiment	+	
	Rootstock and ecological effect on quality	+	
	Rootstock screening		+
Coffee	Breeding	+	
	Pruning and cultural methods as influencing yield	+	
	Mechanical harvesting	+	
Corn	Improvement of strains	+	
	Nutritional value	+	
Crops and Weeds	Weedicide trials	+	+
Cucurbit	Breeding	+	
Grass	Introduction and evaluation	+	+
Guava	Variety selection	+	+
	Growth regulators to study branching, flowering and fruit quality	+	
	Pruning to facilitate mechanical harvesting		+
	Herbicide screening		+
	Nutrition experiment		+

Table 1. (Continued) Ongoing or Completed Research at Malama-Ki and Waiakea Research Stations[a]

Crop	Nature of Research	Waiakea	Malama-Ki
Kikuyu and Pangola grass	Nutrition experiment; nutritional value	+[b]	
Legume and Grass	Nitrogen fixation by legumes and utilization by crops	+	
Lychee	Variety selection		+[b]
	Nutrition experiment	+	
Macadamia	Variety selection		+
	Rootstock selection; disease control; planting density; rootstock-scion influence; nutritive value of nuts	+	
Mango	Variety selection		+
Norfolk Island Pine	Culture and fertilizer trial	+	
Ornamental plants	Cultivation of red ginger, ti, crotons, bird of paradise	+	
Papaya	Breeding; nutrition experiments; weed control;		+
	equipment for mechanical harvesting; disease control	+	+
Passion fruit	Culture and training; disease control		+
	improvement of strains	+	+
Poha	Variety selection; planting density; trellis test	+	
Proteas	Evaluation and management	+	+
Sorghum	Culture; nutritional value	+	
Strawberry guava	Culture	+	

Table 1. (Continued) Ongoing or Completed Research at Malama-Ki and Waiakea Research Stations[a]

Crop	Nature of Research	Waiakea	Malama-Ki
Sugarcane	Micronutrient experiment	+[b]	
Tomato	Disease control; nutrition experiment	+	
	breeding	+	+[b]
Tree crops	Culture and fertilization	+	+
Vegetables	Variety and adoption trials of tomato, cabbage, cauliflower, broccoli, celery, Chinese cabbage, lettuce, radish, peas, carrots, cucumber, melon, sweet corn	+	+

[a]Data obtained from the office of the Assistant Director, Hawaii Agricultural Experiment Station.

[b]Indication of ongoing or completed research at the respective research stations, Hawaii Agricultural Experiment Station.

of the soils. In many instances crops were cultivated for purposes of breeding, pest control and development of farm machinery.

The current state of knowledge suggests that under certain conditions and in certain areas, the forested lava lands of the State have high agricultural potential. There is a need to specify more precisely those conditions which act as constraints for agricultural use and to delineate soil boundaries according to these constraints.

The suitability of Tropofolists for crop production is illustrated by a photograph (Figure 3) of an experimental papaya plot on the Malama-Ki Research Station.

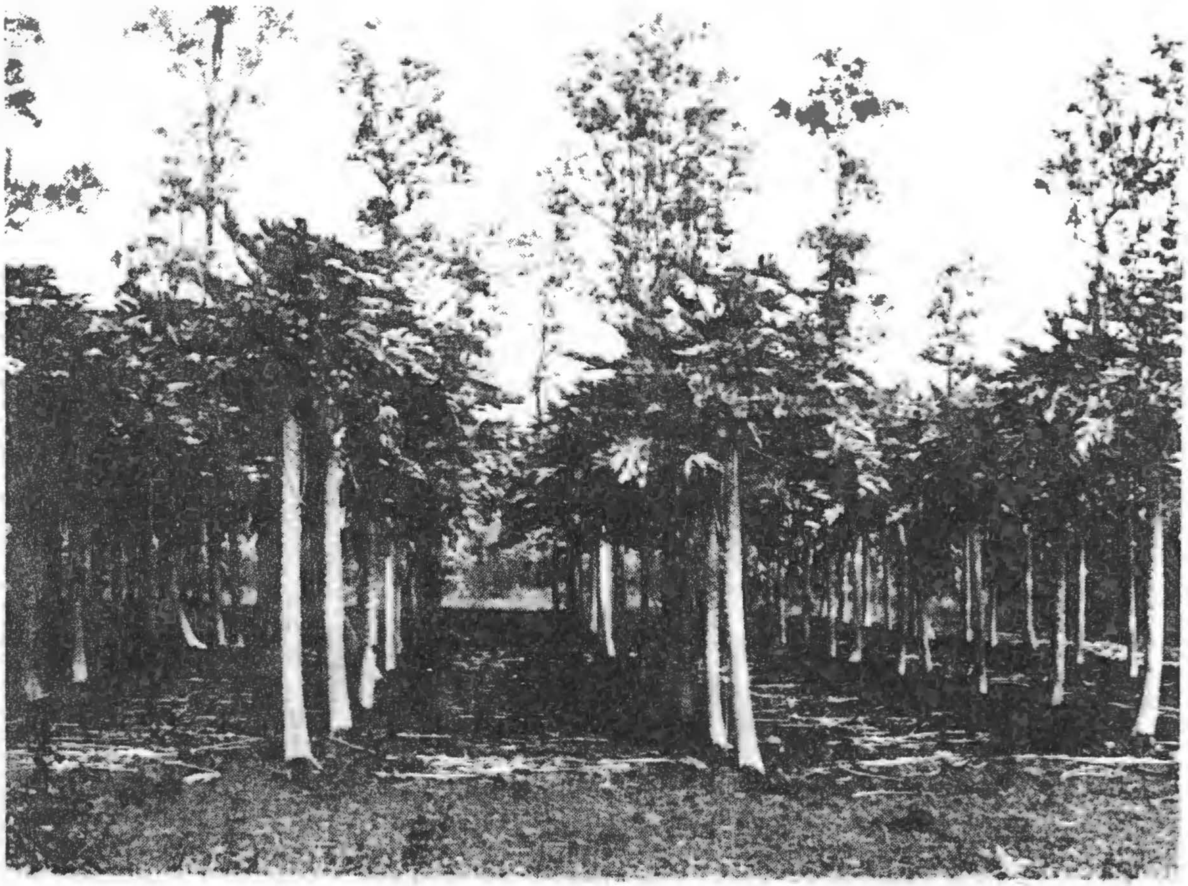

Figure 3. Papaya orchard (front) and Metrosideros forest (rear) on the Malama-Ki Research Station.

MATERIALS AND METHODS

The preliminary soil survey maps of the island of Hawaii along with the soil series descriptions provided by the Soil Conservation Service were used to identify the soils at each sampling site. Wherever possible, the soils were collected in a cultivated area and in an adjoining forest. This procedure was designed so that soils in the natural forest could be compared with those in the cultivated areas. Since almost all of the cultivated Tropofolists are on aa substrate, there was little opportunity to sample lithic (pahoehoe) Tropofolists.

A detailed description of the sampling procedure and the types of analysis run on these samples are given in the following sections.

Soil Collection

At each sampling site, an area equal to 76 by 76 cm (30 by 30 inches) square was marked off and soil materials collected as a function of depth. The sample from each depth increment was separated into three size fractions--rocks with diameter greater than 15 cm (6 inches), rocks with diameter from 1.25 to 15 cm (0.5 to 6 inches), and materials less than 1.25 cm hereafter called 'fines'. Each fraction was weighed and subsamples of fines were taken for laboratory analysis. An example of soil sampling pit is illustrated in Figure 4.

Rock Size Distribution

Two hundred g of fines were separated into particles with diameter between 6 mm and 2 mm by wet sieving. Soil materials of the less than 2 mm size fraction, maintained at the original field

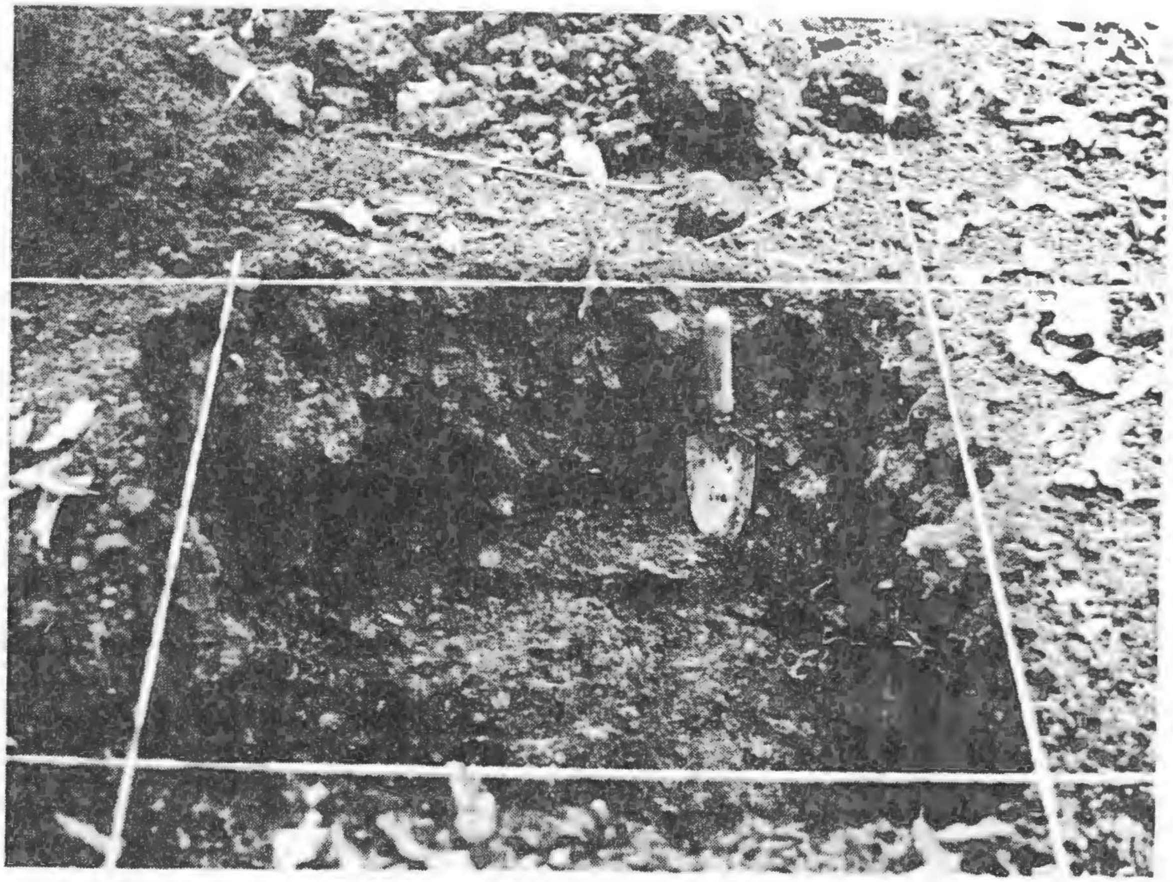

Figure 4. Sampling pit with coarse and medium sized fractions at the top.

moisture, were used for chemical analysis. A few samples were very wet and were dried to a workable consistency before they were sieved. The results of chemical analyses are expressed on moisture free basis.

Bulk Density

Bulk density values were computed by dividing soil mass by the volume from which the soil materials were removed. Bulk density is expressed as grams per cubic centimeter (g/cm^3). Determination of volume was not always possible because of large boulders.

Soil pH

The pH's in water and 1 N KCl solution were measured using a soil to solution ratio of 1:1. The pH in 0.01 M $CaCl_2$ was also determined in a soil to solution ratio of 1:2 (Peech, 1965).

Organic Carbon

Either 50 or 100 mg of soil samples that had previously been ground to pass a 60 mesh sieve were used to determine organic carbon content by the Walkley and Black method (Soil Survey Staff, 1967).

Total Nitrogen

Total nitrogen was determined on a 1 g sample by the Kjeldahl distillation method outlined by Bremner (1965).

Cation Exchange Capacity and Exchangeable Cations

Cation exchange capacity (CEC) was determined on a 10 g sample using 1 N NH_4OAc at pH 7 (Chapman, 1965). Excess NH_4OAc was used to replace exchangeable cations. The excess NH_4^+ was removed by washing with methyl alcohol. The adsorbed NH_4^+ was then displaced with 10% NaCl and distilled in NaOH into Boric acid.

Exchangeable calcium and magnesium were determined in the NH_4^+OAc extract by means of the Perkin-Elmer Model 303 Atomic Absorption Unit. Exchangeable potassium and sodium were determined by means of the Beckman D.U. Flame Spectrometer.

Phosphorus Sorption

Phosphorus sorption curves were constructed using the procedure outlined by Fox and Kamprath (1970).

Expression of Data

Tropofolists are unconventional soils. Laboratory data for these soils when expressed in conventional fashion often give a false picture of the soil. In most soils, measured value represents the average for the entire soil horizon. In Tropofolists consisting of boulders and organic materials, many of the values represent that of the less than 2 mm fraction. The values do not include the mass of the boulders. To avoid this problem soil data is expressed on a volume rather than on a mass basis. Using CEC as an example, the value is expressed as meq per liter (1) rather than meq/100 g of a soil. For comparison values of two conventional soils are provided.

RESULTS AND DISCUSSION

Size Distribution

The size distribution of soil materials is presented in Table 2. Unlike conventional soils, Tropofolists are largely made up of particles greater than two millimeters in diameter. This is due to the recent origin of aa and pahoehoe rocks. The cultivated samples had a higher proportion of medium sized (1.25 to 15 cm) rocks than <1.25 cm size fraction for all depths examined. This difference is probably real. During the land clearing operation with heavy bulldozers, there is considerable fracturing of the large boulders (see Figure 14).

No other particular trend in size distribution could be detected. Spot-checks of many sites in the forests and cultivated areas confirmed the wide variation in rock texture. This variation in texture can be readily seen along road cuts (see Figure 6). These variations probably contribute to differences in crop performances.

Bulk Density

Bulk density data are presented in Table 2. The bulk density values from cultivated areas varied from 0.38 to 2.32 g/cm^3. The average value for cultivated areas of Honomalino was about 1 g/cm^3 while that at Malama-Ki and Kalapana was about 1.2 g/cm^3. The lower bulk density values are the result of loose packing of fine organic and inorganic materials. The higher bulk density values are caused by close packing of rocks or presence of large boulders.

Bulk density values of forest samples varied from 0.5 to 1.0 g/cm^3.

Table 2. Rock Size Distribution and Bulk Density Values of Samples Collected from a 76 x 76 cm Square Area

Sample Location	Profile No.	Depth cm	Greater than 15 cm		1.25 to 15 cm		Less than 1.25 cm		0.6 to 1.25 cm		0.2 to 0.6 cm		Less than 0.2 cm		Bulk Density g/cm^3
			%	g/l	%	g/l	%	g/l	%	g/l	%	g/l	%	g/l	
Honomalino															
Low elevation															
Cultivated	1	0-5	6.0	79	66.3	876	27.7	376	2.9	39	5.1	68	19.7	269	1.32
		5-13	23.7	187	52.4	413	23.9	192	3.1	25	3.1	24	17.7	143	0.78
		13-25	0.0	0	52.3	100	47.7	92	8.8	17	7.4	14	31.5	61	0.38
"	2	0-5	36.0	482	49.2	658	14.8	201	3.2	43	3.2	43	8.4	115	1.34
		5-13	65.5	782	34.5	411	0.0	0	0.0	0	0.0	0	0.0	0	1.19
		13-25	100.0	65	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	-
Forest	1	0-13	0.0	0	54.4	205	45.6	174	4.5	17	15.7	59	25.4	98	0.37
"	2	0-15	0.0	0	59.0	267	41.0	233	3.2	15	2.8	13	35.0	205	0.45
Medium elevation															
Cultivated	1	0-8	23.2	527	64.7	1385	12.1	260	1.6	35	2.8	59	7.7	166	2.32
		8-18	2.6	31	74.9	901	22.5	273	8.4	102	4.8	57	9.3	114	1.48
		18-51	13.9	66	59.0	281	27.1	138	8.7	41	4.0	27	14.4	70	0.72
"	2	0-8	4.9	78	84.0	1332	11.1	176	3.8	61	2.0	31	5.3	84	1.60
		8-25	19.0	181	62.9	598	18.1	174	4.1	39	3.1	29	10.9	106	0.94
		25-51	8.8	76	68.2	587	23.0	199	8.4	72	4.4	38	10.2	89	0.85
"	3	0-15	38.3	267	27.7	193	34.0	242	5.5	38	2.7	19	25.8	185	0.69
		15-30	3.4	26	54.7	417	41.9	325	11.3	86	8.6	66	22.0	173	0.76
		30-36	47.3	520	20.5	226	32.2	322	18.7	205	9.0	99	4.5	18	0.42
"	4	0-8	0.0	0	81.5	1343	18.5	307	6.9	113	3.2	52	8.4	142	1.63
		8-20	0.0	0	77.2	1080	22.8	318	14.0	196	7.0	97	1.8	25	1.39
		20-38	6.1	57	73.4	674	20.5	190	9.9	91	5.6	52	5.0	47	0.92
"	5	0-3	16.1	294	83.9	1524	0.0	0	0.0	0	0.0	0	0.0	0	1.77
		3-10	0.0	0	78.3	1385	21.7	386	8.7	154	5.3	94	7.4	138	1.74
		10-25	5.4	57	80.8	851	13.8	146	4.9	51	2.6	28	6.3	67	0.80
		25-41	3.9	25	90.0	676	6.7	50	2.0	15	1.1	8	3.6	27	0.74
"	6	0-3	9.2	241	90.8	2354	0.0	0	0.0	0	0.0	0	0.0	0	1.96
		3-20	26.6	255	59.9	575	13.5	130	6.0	58	2.1	20	5.4	52	0.95
		20-38	17.5	135	68.7	528	13.8	106	5.5	42	1.6	13	6.7	51	0.76

Table 2. (Continued) Rock Size Distribution and Bulk Density Values of Samples Collected from a 76 x 76 cm Square Area

Sample Location	Profile No.	Depth cm	Greater than 15 cm		1.25 to 15 cm		Less than 1.25 cm		0.6 to 1.25 cm		0.2 to 0.6 cm		Less than 0.2 cm		Bulk Density g/cm^3
			%	g/l	%	g/l	%	g/l	%	g/l	%	g/l	%	g/l	
Forest	1	0-8	0.0	0	65.9	256	34.1	136	3.6	14	0.9	4	29.6	118	0.39
		8-13	0.0	0	75.1	500	24.9	171	1.7	11	1.7	12	21.5	148	0.66
"	2	0-8	0.0	0	38.7	98	61.3	156	0.6	2	4.8	12	55.9	142	0.25
		8-13	0.0	0	27.6	155	72.4	423	1.0	6	1.0	6	70.4	411	0.56
<u>Honomalino</u>															
High elevation Cultivated	1	0-5	0.0	0	52.7	597	47.3	547	10.1	114	7.2	81	30.0	352	1.13
		5-13	0.0	0	60.3	70	39.7	46	11.9	14	6.4	7	21.4	25	-
"	2	0-8	0.0	0	79.0	493	21.0	433	1.9	11	0.7	4	18.4	118	0.62
		8-20	0.0	0	73.9	362	26.1	131	2.2	11	2.2	11	21.7	109	0.49
		20-30	0.0	0	76.3	400	23.7	127	4.1	21	3.0	16	16.6	90	0.52
"	3	0-8	0.0	0	64.7	397	35.3	217	9.9	60	7.5	45	17.9	112	0.85
Forest	1	0-8	8.3	0	57.2	70	34.5	292	1.4	11	1.1	9	32.0	272	0.82
		8-15	0.0	0	79.8	693	20.2	176	7.4	64	2.4	21	10.4	91	0.85
"	2	0-15	0.0	0	45.2	209	54.8	285	1.2	6	1.5	7	52.1	272	0.46
		15-23	0.0	0	56.2	98	43.8	97	1.8	3	1.6	3	40.4	91	0.17
<u>Keaau</u>															
Cultivated	1	0-10	34.2	681	45.6	908	20.2	406	6.2	124	6.3	125	7.7	157	1.99
		10-20	40.2	774	42.6	814	17.5	337	8.2	158	4.6	88	4.7	91	1.92
		20-30	21.7	431	58.5	1158	19.8	396	5.4	106	4.5	90	5.9	200	1.98
		30-46	0.0	0	69.7	290	30.3	145	9.4	40	7.4	33	13.5	72	0.52
"	2	0-15	47.7	709	47.7	709	4.6	68	1.5	22	1.2	18	1.9	28	1.42
		15-30	54.9	752	37.7	517	7.4	101	1.6	22	1.8	25	4.0	54	1.82
		30-46	65.9	641	24.6	240	9.5	90	2.2	21	2.4	23	4.9	46	0.96
"	3	0-15	24.9	355	57.9	824	17.2	247	4.0	57	4.5	63	8.7	127	1.42
		15-31	20.4	301	66.6	982	13.0	192	3.5	51	2.4	35	7.1	106	1.46
		31-51	0.0	0	88.0	790	12.0	109	3.1	28	2.2	19	6.7	62	1.00
Forest	1	0-10	0.0	0	89.8	948	10.2	108	3.4	36	1.4	14	5.4	58	1.05
		10-20	4.3	62	88.4	1267	7.3	105	2.2	32	1.2	16	3.9	57	1.43
		20-33	2.9	31	83.0	860	14.1	148	3.7	39	1.8	18	8.6	91	1.03
		33-46	6.9	36	76.4	393	16.7	85	5.6	28	3.0	15	8.1	42	0.51

Table 2. (Continued) Rock Size Distribution and Bulk Density Values of Samples Collected from a 76 x 76 cm Square Area

Sample Location	Profile No.	Depth cm	Greater than 15 cm		1.25 to 15 cm		Less than 1.25 cm		0.6 to 1.25 cm		0.2 to 0.6 cm		Less than 0.2 cm		Bulk Density g/cm^3
			%	g/l	%	g/l	%	g/l	%	g/l	%	g/l	%	g/l	
Cultivated	4	0-15	0.0	0	72.1	965	27.9	377	5.9	78	9.4	125	12.6	174	1.34
		15-30	17.4	177	64.2	652	18.4	169	4.3	34	5.4	44	8.7	91	1.27
		30-46	17.6	117	61.1	406	21.3	144	4.8	32	6.3	42	10.2	70	0.73
"	5	0-15	10.0	0	70.9	850	29.1	352	7.5	89	11.0	132	10.6	131	1.20
		15-30	14.3	167	60.9	709	24.8	192	8.5	100	9.8	114	6.5	78	1.28
		30-46	6.8	48	70.8	504	22.4	188	7.4	53	8.7	62	6.3	73	1.18
"	6	0-5	0.0	0	67.3	689	32.7	240	7.5	76	7.0	71	18.2	193	1.02
		5-20	11.1	209	75.5	1419	32.4	153	4.1	77	3.4	64	5.9	112	1.88
		20-36	5.4	64	86.4	1016	8.2	96	2.4	29	1.4	16	4.4	51	1.16
"	7	0-8	14.9	196	78.1	1036	7.0	92	1.5	20	1.5	20	4.0	52	1.31
		8-18	8.4	156	86.4	1596	5.2	94	1.7	31	1.1	21	2.4	42	1.84
		18-36	24.6	131	61.5	327	13.9	73	3.1	16	3.1	16	7.7	41	0.53
		36-51	8.6	41	87.0	417	4.4	20	0.9	4	0.9	4	2.6	12	0.48
"	8	0-5	0.0	0	15.7	155	84.3	850	8.1	79	16.3	160	59.9	611	0.98
		5-15	0.0	0	68.7	759	31.3	351	7.4	82	7.4	81	16.5	188	1.10
"	9	0-3	0.0	0	2.5	29	97.5	1140	9.9	114	19.9	231	67.7	795	1.13
		3-20	20.7	224	54.0	580	25.3	174	6.3	68	5.1	55	13.9	151	1.06
<u>Malama-Ki</u> Cultivated	1	0-8	0.0	0	100.0	739	0.0	0	0.0	0	0.0	0	0.0	0	0.73
		8-20	0.0	0	83.1	1217	16.9	246	5.2	76	7.4	107	4.3	63	1.45
		20-33	9.4	126	84.7	1139	5.9	78	2.0	26	1.8	24	2.1	28	1.34
Forest	1	0-31	51.2	201	46.7	184	2.1	9	0.1	1	0.2	1	1.8	7	0.41
		31-61	22.7	78	73.0	250	4.3	14	1.6	5	1.3	5	1.4	4	0.68
<u>Kalapana</u> Cultivated	1	0-15	10.9	88	57.2	464	31.3	262	12.0	97	6.3	51	13.6	114	0.81
		15-30	38.9	567	47.8	697	13.3	195	4.1	59	3.2	47	6.0	89	1.45
		30-45	36.8	397	52.5	563	10.8	116	3.1	33	3.1	34	4.6	49	1.07
"	2	0-45	26.3	266	69.4	701	4.3	43	1.8	18	1.0	10	1.5	15	1.01

The range in bulk density from 0.38 to 2.32 g/cm^3 provides a good illustration of the extreme variability in the particle size distribution and packing of the rocks (see Figure 5). In general there is closer packing in cultivated soils than in forest, and this is reflected in the higher bulk densities in the cultivated soils. Closer packing of rock fragments and the entrapment of organic matter between the rocks probably improves the quality of the cleared land for crop production.

The fines were further subdivided into three fractions. The size fractions between 1.25 to 0.6 cm and 0.6 to 0.2 cm contribute to water retention as will be shown in a later section. The quantity of small clinkers and fines is a good index of the potential for crop production of a Tropofolist. Unfortunately rock texture is a highly variable parameter even within a small area on the same lava flow. The profile shown in Figure 5 illustrates a soil which would be considered ideal for crop production, and Figure 6 shows a section of a lava flow which would be difficult to cultivate.

Most of the organic matter resides in the less than 2 mm fraction. Soil samples collected from Honomalino orchard had an average value of 109 g/l, whereas Keaau macadamia orchard had 93 g/l. Malama-Ki and Kalapana orchards had 62 and 66 g/l, respectively. Soil samples collected from forest adjoining the macadamia orchard in Honomalino had about 176 g/l. The mean value from a forest site near Keaau orchard was about 62 g/l. Only about 5.5 g of the 2 mm size fraction per liter were measured in the Malama-Ki forest.

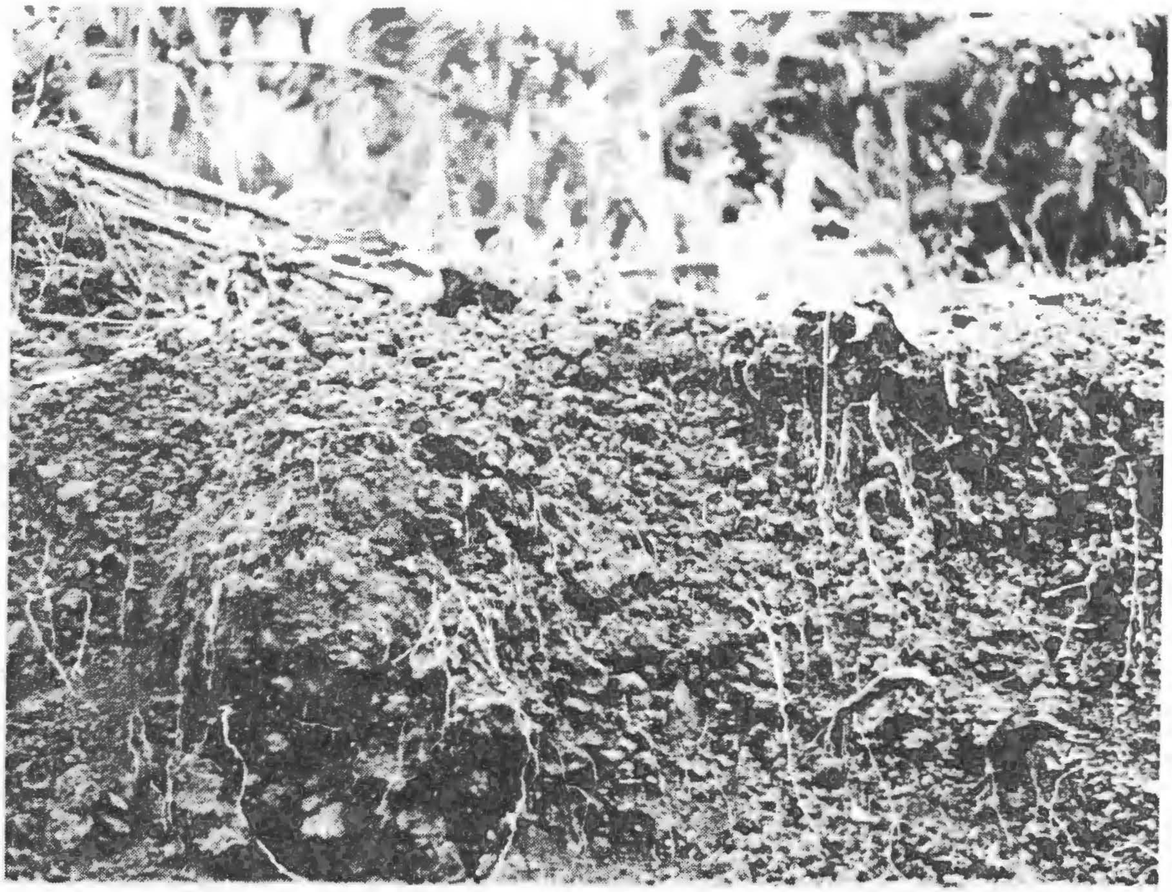

Figure 5. Forested aa land with loose clinkery materials.

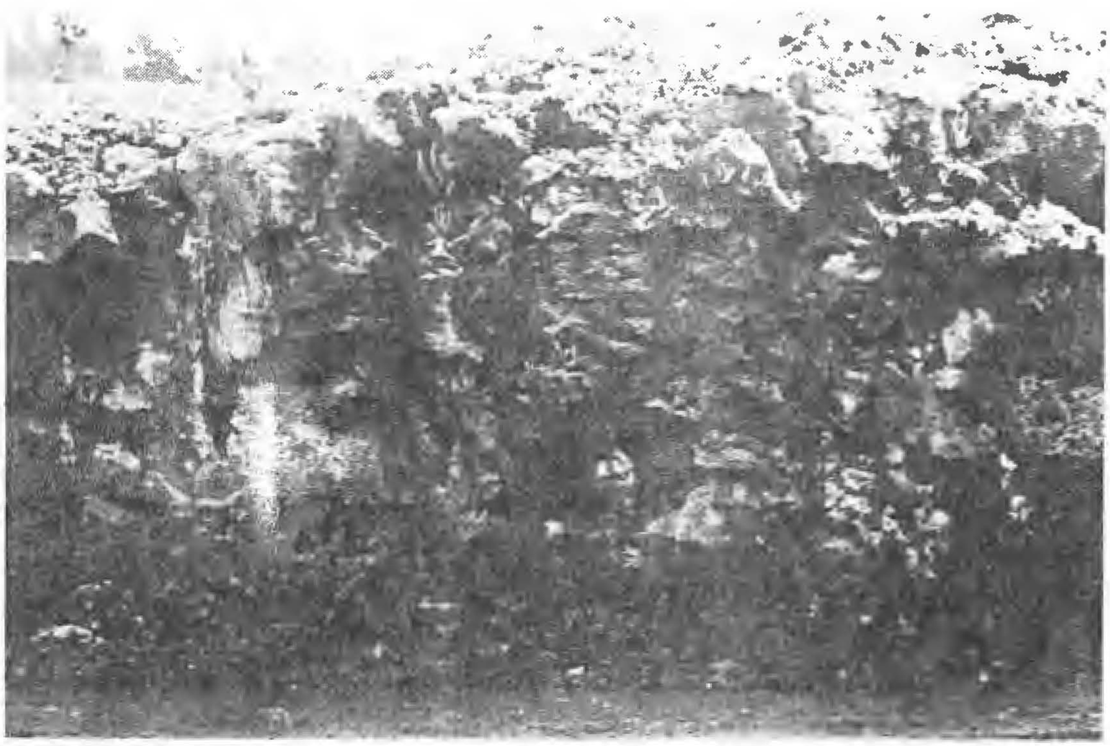

Figure 6. A section of the 1955 Kilauea aa lava flow showing heavy lichens growth and young Metrosideros on dense massive rocks underlain by fine clinkers.

Organic Carbon Distribution

The organic carbon contents of each sampling depth are presented in Table 3. Organic carbon in Table 3 represents the carbon content of less than 2 mm size fraction. While the values are high in this fraction, the quantity of fines in a given volume of soil is small, thus when the organic carbon content is expressed on a volume basis (g/l), the values approach those of inorganic soils.

Organic carbon contents of two inorganic soils are presented in Table 5.

The Hilo series (Typic Hydrandept) has about 50 g of organic carbon per 1000 cm^3 of soil in the top 38 cm, and the Molokai series (Typic Torrox) contains about 21 g/1000 cm^3.

Most of the Honomalino orchard soil samples are comparable to the Molokai series in organic carbon content. Keaau orchard samples contained less than half that of the Honomalino orchard, and the Kalapana and Malama-Ki orchards registered even lower values.

Surprisingly, even the forest samples did not have carbon content comparable to that of the Hilo series. This is due to the rapid drop in organic matter content with depth in Tropofolists.

Clearing and preparation of the land for cultivation drastically alter the distribution pattern of coarse rocks and fines including the organic matter. The data also show that the disappearance of organic matter in cultivated fields is only apparent. Organic matter is redistributed to lower depths in cleared fields and the presence of organic matter below the surface even after many years of cultivation suggests that organic carbon content is not reduced by land clearing.

Table 3. Organic Carbon and pH Values of Less Than 2 mm Size Fraction

Sample Location	Profile No.	Depth cm	Organic Carbon %	Organic Carbon g/l[a]	pH H_2O	pH KCl	pH $CaCl_2$
Honomalino							
Low elevation							
Cultivated	1	0-5	24.73	66.52	6.7	5.8	6.3
		5-13	20.91	29.69	7.1	6.0	6.6
		13-25	19.19	23.42	6.9	5.9	6.3
"	2	0-5	15.02	17.27	7.0	5.9	6.6
Forest	1	0-13	26.24	25.72	6.9	5.91	6.8
"	2	0-15	24.01	49.22	6.8	5.9	6.5
Medium elevation							
Cultivated	1	0-8	22.74	41.94	6.7	6.0	6.4
		8-18	17.64	25.13	6.8	6.0	6.4
		18-51	24.69	26.58	6.9	6.0	6.3
"	2	0-8	23.89	20.06	7.5	6.9	7.2
		8-25	21.40	22.68	7.0	6.1	6.9
		25-51	15.09	13.43	7.2	6.3	6.9
"	3	0-15	26.67	49.34	6.9	6.1	6.5
		15-30	23.08	39.93	7.1	6.6	6.8
		30-36	17.07	3.07	7.6	6.8	7.0
"	4	0-8	21.84	31.01	6.1	5.9	6.1
		8-20	16.48	4.12	6.2	5.7	6.0
		20-38	15.32	7.20	6.7	5.8	6.0
"	5	0-3	0.0	0.0	-	-	-
		3-10	15.60	21.53	6.6	6.2	6.5
		10-25	14.19	9.50	7.2	6.4	6.9
		25-41	15.62	4.32	7.3	6.5	6.9
"	6	0-3	0.0	0.0	-	-	-
		3-20	15.87	8.25	7.0	6.5	6.7
		20-38	17.98	9.16	7.1	6.6	6.7
Forest	1	0-8	29.31	34.59	6.4	5.8	6.1
		8-13	23.74	35.14	6.2	5.7	5.9
"	2	0-8	32.89	46.70	6.1	5.6	5.8
		8-13	21.52	88.44	6.1	5.6	5.8

Table 3. (Continued) Organic Carbon and pH Values of Less Than 2 mm Size Fraction

Sample Location	Profile No.	Depth cm	Organic Carbon %	Organic Carbon g/l[a]	pH H_2O	pH KCl	pH $CaCl_2$
Honomalino							
High elevation							
Cultivated	1	0-5	19.40	68.28	7.0	6.4	6.8
		5-13	17.85	4.46	7.1	6.5	6.7
"	2	0-8	21.59	25.47	7.3	6.6	7.1
		8-20	19.68	21.45	7.8	7.1	7.4
		20-30	19.02	17.11	7.6	7.1	7.3
"	3	0-8	15.03	16.83	6.4	6.0	6.4
Forest	1	0-8	29.19	79.40	6.0	5.5	5.8
		8-15	21.09	19.19	5.9	5.6	5.7
"	2	0-15	26.29	65.40	5.6	5.4	5.6
		15-23	19.10	6.11	5.6	5.4	5.6
Keaau							
Cultivated	1	0-10	7.90	12.40	4.6	4.4	4.5
		10-20	9.41	8.56	4.8	4.5	4.6
		20-30	9.35	18.70	5.2	4.8	4.9
		30-46	11.87	9.49	5.3	5.0	5.3
"	2	0-15	8.39	2.35	4.4	4.1	4.2
		15-30	8.12	4.39	4.5	4.2	4.3
		30-46	5.81	2.67	5.3	5.0	5.2
"	3	0-15	7.88	10.00	4.4	4.1	4.3
		15-31	9.64	10.21	4.7	4.4	4.6
		31-51	13.46	8.34	5.2	4.8	5.1
Forest	1	0-10	22.11	12.82	6.0	5.3	5.1
		10-20	22.36	12.74	6.0	5.3	5.7
		20-33	19.54	17.78	6.0	5.3	5.8
		33-46	20.41	8.57	6.0	5.4	5.6
Cultivated	4	0-15	5.64	9.81	5.3	4.5	4.7
		15-30	4.44	5.05	5.4	4.6	4.8
		30-46	7.34	5.71	5.6	4.7	5.1
"	5	0-15	5.58	7.30	4.8	4.2	4.4
		15-30	4.97	3.87	5.3	4.5	4.7
		30-46	2.70	1.97	5.8	4.8	5.0
Forest	2	0-15	47.87	-	6.0	5.6	5.8

Table 3. (Continued) Organic Carbon and pH Values of Less Than 2 mm Size Fraction

Sample Location	Profile No.	Depth cm	Organic Carbon		pH		
			%	g/l[a]	H_2O	KCl	$CaCl_2$
Keaau							
Cultivated	6	0-5	13.38	25.82	5.0	4.3	4.9
		5-20	10.99	12.30	5.2	4.5	4.6
		20-36	12.91	6.58	5.1	4.6	4.7
"	7	0-8	30.87	16.05	4.3	3.9	4.2
		8-18	18.12	7.61	4.5	4.0	4.3
		18-36	17.23	7.06	4.9	4.4	4.7
		36-51	14.47	1.73	5.5	4.8	5.1
"	8	0-5	3.91	23.89	5.7	4.3	4.8
		5-15	5.71	10.73	5.8	4.8	5.2
"	9	0-3	4.73	37.60	4.8	4.1	4.4
		3-20	8.65	13.06	5.3	4.6	4.9
Malama-Ki							
Cultivated	1	0-8	0.0	0.0	-	-	-
		8-20	4.80	3.02	5.7	5.2	5.3
		20-33	4.72	1.32	5.8	5.2	5.6
Forest	1	0-31	42.48	3.86	5.0	4.3	4.6
		31-61	18.69	3.16	5.6	4.8	5.1
Kalapana							
Cultivated	1	0-15	6.61	7.54	4.9	4.5	4.7
		15-30	6.08	5.41	5.4	5.0	5.1
		30-45	7.52	3.68	5.5	5.1	5.3
"	2	0-45	10.08	1.51	4.1	3.8	3.9
Forest	1	0-10	50.19	-	5.5	5.1	5.4

[a]Computed on the basis of whole soil.

In general volumetric organic matter content is positively correlated to the quantity of fines in that volume.

Soil pH

Table 3 shows the pH values of the soil samples. The pH values in 0.01 M $CaCl_2$ solution of Honomalino forest samples varied from 5.6 to 6.8; whereas the adjacent cultivated field had soil pH values which ranged from 6.0 to 7.4. Soil samples of Keaau, Malama-Ki and Kalapana were strongly acidic, ranging in pH from 3.9 to 5.8.

At Kalapana and Keaau the forest sites adjoining the orchard had slightly higher pH values. The lower pH values of the orchard is most likely due to application of ammoniacal fertilizers. In the Keaau, Kalapana and Malama-Ki samples the surface horizons were more acidic than the subsurface horizons.

Total Nitrogen

Total nitrogen contents are presented in Table 4 as g/l. The Hilo and Molokai soils contain an average value of 2.2 g/l of nitrogen down to a depth of 38 cm. The nitrogen content of Honomalino orchard samples varied from 0.18 to 4.44 g/l and are comparable to the Molokai and Hilo soils. The percent nitrogen in the fine fraction does not vary greatly with depth, but when nitrogen is expressed on a volume basis, a marked decrease is noted. This reduction in nitrogen is due to decrease in the fines with depth. The nitrogen content of the adjoining forest samples varied from 1.2 to 4.8 g/l.

Table 4. Total Nitrogen and Cation Exchange Capacity

Site Location	Profile No.	Depth cm	Nitrogen		CEC		Exchangeable Cations meq/l				Base saturation %
			%	g/l	meq/100 g	meq/l	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	
Honomalino											
Low elevation											
Cultivated	1	0-15	1.45	3.90	66.56	179.05	24.78	9.41	4.84	1.69	147.35
		5-13	1.36	1.93	72.50	109.95	72.70	4.79	2.82	0.89	78.89
		13-25	1.18	1.44	53.66	65.46	42.20	2.24	1.74	1.30	77.13
Forest	1	0-13	1.48	1.45	80.28	78.67	46.35	3.62	2.08	0.42	66.71
Medium elevation											
Cultivated	1	0-8	1.17	2.15	55.91	103.12	90.16	6.12	3.34	4.17	76.33
		8-18	0.94	1.34	57.34	81.70	63.84	3.06	2.32	0.94	85.87
		18-51	1.17	1.26	73.32	78.95	63.23	2.62	2.34	1.44	88.39
"	3	0-15	1.24	2.29	100.29	186.79	156.32	5.95	5.21	1.12	90.27
		15-30	1.38	2.39	99.94	172.90	165.85	3.87	5.32	0.88	101.76
		30-36	1.02	0.18	73.52	13.23	16.51	0.26	0.51	0.09	131.42
"	5	0-3	-	-	-	-	-	-	-	-	-
		3-10	0.78	1.08	54.68	75.46	62.03	3.31	2.45	0.63	90.69
		10-25	0.72	0.48	52.63	35.26	33.50	1.09	1.62	0.16	103.31
		25-41	0.87	0.23	62.67	16.92	17.32	0.53	0.63	0.08	109.81
Forest	1	0-8	1.65	1.94	96.67	114.07	77.95	4.96	2.63	0.66	75.57
		8-13	1.50	2.22	89.09	131.85	85.47	5.68	4.17	0.82	72.97

Table 4. (Continued) Total Nitrogen and Cation Exchange Capacity

Site Location	Profile No.	Depth cm	Nitrogen		CEC		Exchangeable Cations meq/l				Base saturation %
			%	g/l	meq/100 g	meq/l	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	
High elevation											
Cultivated	1	0-5	1.26	4.44	78.03	274.67	274.38	8.90	8.23	0.98	106.49
		5-13	1.16	0.29	83.15	20.78	17.61	0.67	0.53	0.13	91.19
Forest	1	0-8	1.72	4.68	134.76	366.55	174.76	9.98	6.36	2.42	52.79
		8-15	1.23	1.20	88.47	80.51	49.41	2.77	2.19	0.30	67.92
<u>Keaau</u>											
Cultivated	1	0-10	0.54	0.85	52.43	82.31	7.22	1.33	0.91	0.23	11.78
		10-20	0.36	0.33	21.50	19.57	3.82	0.28	0.32	0.09	23.11
		20-30	0.54	1.08	33.38	66.76	19.10	1.06	1.08	0.24	32.17
		30-56	0.60	0.48	45.06	36.04	12.08	0.60	0.55	0.20	37.26
Forest	1	0-10	0.96	0.56	123.49	71.62	28.62	2.41	1.04	0.09	44.93
		10-20	1.02	0.58	100.76	57.43	22.39	1.53	0.81	0.01	43.11
		20-33	1.29	1.17	119.60	108.84	28.84	1.79	1.11	0.22	29.38
		33-46	1.14	0.48	99.94	41.97	12.24	0.53	0.46	0.07	31.70
Cultivated	4	0-15	0.21	0.37	20.48	35.64	5.41	0.29	0.52	1.77	22.46
		15-30	0.21	0.24	23.14	26.33	2.54	0.12	0.33	1.43	16.98
		30-46	0.36	0.28	24.17	18.80	4.83	0.27	0.21	0.03	28.46
Forest	2	0-15	2.58	-	177.15	-	-	-	-	-	71.00

Table 4. (Continued) Total Nitrogen and Cation Exchange Capacity

Site Location	Profile No.	Depth cm	Nitrogen %	Nitrogen g/l	CEC meq/100 g	CEC meq/l	Exchangeable Cation meq/l Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Base saturation %
Cultivated	6	0-5	0.69	1.33	48.13	92.89	20.94	1.23	1.33	0.48	25.82
		5-20	0.51	0.55	51.20	57.34	7.67	0.60	0.67	0.19	15.93
		20-36	0.51	0.26	45.06	22.98	3.47	0.25	0.31	0.06	17.88
"	8	0-5	0.12	0.73	18.43	112.60	27.55	1.58	3.97	2.62	31.74
		5-15	0.24	0.45	23.96	45.04	13.44	0.54	1.22	0.47	34.80
<u>Malama-Ki</u>											
Cultivated	1	0-8	-	-	-	-	-	-	-	-	-
		8-20	0.15	0.09	11.26	7.09	3.65	0.13	0.27	0.80	68.56
		20-33	0.15	0.04	12.49	3.58	1.83	0.07	0.13	0.28	66.45
Forest	1	0-31	1.65	0.13	99.12	7.30	3.57	0.33	0.22	0.09	57.64
		31-61	0.93	0.06	119.60	9.56	1.78	0.20	0.13	0.05	22.70
<u>Kalapana</u>											
Cultivated	1	0-15	0.24	0.27	11.06	12.61	8.20	0.39	0.55	0.06	73.23
		15-30	0.26	0.23	11.06	9.84	6.98	0.32	0.40	0.04	78.75
		30-45	0.36	0.18	14.95	7.73	4.90	0.23	0.59	0.02	78.46
Forest	1	0-10	1.72	-	115.51	-	-	-	-	-	66.05

Keaau orchard soil samples registered nitrogen contents from 0.24 to 1.38 g/l. The Kalapana and Malama-Ki orchard samples had less than 0.3 g/l of nitrogen.

Cation Exchange Capacity

The cation exchange capacity, exchangeable cations and the base saturation data are presented in Table 4. Values for the Hilo and Molokai series are also presented in Table 5 for comparison. The Hilo series has an average CEC value of 300 meq/l down to a depth of 38 cm, whereas the Molokai series has about 260 meq in the first 15 cm but decreases to 230 meq in the 15 to 38 cm depth.

Cation exchange capacities of Tropofolists were high and comparable to the Hilo or Molokai soils only in the surface samples from Honomalino. The subsoil samples from Honomalino and all other samples had lower cation exchange capacities. The Malama-Ki and Kalapana soil samples had less than 5% of the CEC of the Molokai soil.

These low CEC values in Tropofolists explain the need for the frequent and heavy fertilizer applications of Tropofolists.

Exchangeable Cations. The Molokai soil has about 58 meq/l of calcium in the top 38 cm while the Hilo soil has about one-tenth that of the Molokai series. In comparison Honomalino orchard is well supplied with bases. Samples from Keaau orchard had 2.54 to 27.55 meq/l, and Malama-Ki and Kalapana orchards had less than 10 meq/l of calcium in the soil.

Table 5. Organic Carbon, Nitrogen and Cation Exchange Capacity of Molokai and Hilo Series

Soil Series	Depth cm	Organic Carbon g/1	Total Nitrogen		CEC meq/1	Exchangeable Cations meq/1			
			g/1	%		Ca^{++}	Mg^{++}	Na^{+}	K^{+}
Molokai	0-15	21.12	2.20	0.20	258.50	66.00	33.00	2.86	4.73
	15-38	21.67	2.05	0.19	229.90	58.30	34.10	2.75	1.43
	38-65	5.50	0.72	0.07	127.60	33.00	24.20	6.93	0.33
	65-100	5.50	0.55	0.50	158.40	35.20	27.50	15.07	0.44
	100-150	2.64	-	-	112.20	22.00	19.80	9.90	0.88
Hilo	0-38	50.23	2.29	0.34	295.32	6.00	1.58	1.31	0.55
	38-96	13.72	1.02	0.32	143.36	1.15	0.54	2.33	0.16
	96-152	11.78	0.52	0.16	144.02	1.29	0.41	1.52	0.15
	152-157	10.29	0.33	0.11	180.50	0.76	0.19	0.72	0.07

Relations Among Chemical Parameters

In most soil materials with coarse inorganic particles, one can expect the cation exchange capacity to depend on the organic matter content. In addition the total nitrogen content would be expected to follow organic matter content. These expectations are clearly borne out as shown by the high correlation (Table 6) between cation exchange capacity and organic carbon and nitrogen and organic carbon. When the correlation analyses are made separately for cultivated and forested areas, the correlation coefficients are higher in the cultivated than in the forested area. There are two possible explanations for the result.

The organic carbon values of samples from the forests are all high and bunched in a narrow range. This is indicated by the large values for the intercepts of the regression equation which relates cation exchange capacity to organic carbon. The intercept is a measure of cation exchange capacity of the inorganic fraction and the large value obviously does not correctly reflect the true situation.

The relation between cation exchange capacity and organic carbon is more correctly represented by samples from cultivated fields. Samples collected from cultivated areas contained a wider range of organic carbon, thus providing the basis for developing a better picture of the relation between cation exchange capacity and organic carbon. The intercept of 1.7 meq indicating a low cation exchange capacity of the inorganic fraction is quite reasonable.

Table 6. Relations Among Chemical Parameters of Less Than 2 mm Size Fraction

Independent Variable	Dependent Variable		No. of obser-vations	Correlation Coefficient	Regression Equation
Organic carbon	Nitrogen	Cultivated	31	0.967**	N = -0.0932 + .0598 (C)
		Forest	13	0.803**	N = 0.0517 + .0325 (C)
		Combined	44	0.931**	N = 0.0788 + .0473 (C)
Organic carbon	CEC	Cultivated	31	0.901**	CEC = 1.748 + 3.393 (C)
		Forest	13	0.434	CEC = 81.915 + 1.017 (C)
		Combined	44	0.844**	CEC = 11.380 + 3.051 (C)
Nitrogen	CEC	Cultivated	31	0.915**	CEC = 7.738 + 55.728 (N)
		Forest	13	0.559*	CEC = 64.630 + 32.022 (N)
		Combined	44	0.889**	CEC = 7.505 + 63.175 (N)
Base saturation	pH	Cultivated	31	0.861**	pH = 4.348 + 0.0206 (B.S.)
		Forest	13	0.383	pH = 5.0334 + 0.0113 (B.S.)
		Combined	44	0.805**	pH = 4.4653 + 0.0195 (B.S.)

The second reason for the poor correlation between cation exchange capacity and organic carbon in the forest sample may lie in the higher content of partially decomposed organic litter. Fresh litter does not possess the high exchange capacity of humus, and a highly variable litter content can cause the correlation to be poor.

The data, in any case, show that cation exchange capacity, total nitrogen and organic carbon are highly interrelated.

Another expected relation is the one between pH and base saturation. As more of the exchange sites are occupied by bases one can expect the acidity of the soil solution to decrease. This expectation is confirmed by the positive correlation between soil pH and base saturation.

A pH value of 4.47 is noted for the intercept of the equation which relates pH to base saturation for all samples from forest and cultivated fields. This is very close to the pH value of 4.5 used to separate dysic from euic soil families in Tropofolists.

Summer Rainfall Versus Winter Rainfall Belts. A pattern develops when soil chemical characteristics of samples from the Kona district (Honomalino) are compared with those from the Puna-Hilo district (Keaau, Malama-Ki, Kalapana). The samples from Kona have higher organic carbon content in the fines, higher pH, higher CEC and are richer in bases.

Two factors can account for these differences. Samples in Kona were collected from the 1000 to 2000 feet elevation zone. In the Puna-Hilo district the elevations were well below 500 feet elevation.

In Kona rainfall was less than 80 inches and in Hilo greater than 80 inches per year. In addition rainfall maximum appears in the summer months in Kona and in the winter months in Hilo and Puna.

Phosphorus

Of the three major elements (N, P, K) required by plants, phosphorus is the least mobile in soils. Most soils of Hawaii have great affinity for this element, and large quantities, often in excess of 1000 pounds per acre, must be applied to a soil before this element appears in the soil solution in sufficient concentration to supply needs of agronomic crops. Organic matter and coarse aa lava rocks however are not expected to immobilize phosphorus as readily as inorganic clays.

The affinity of a soil material for phosphorus can be measured by determining phosphorus adsorption isotherms. The isotherms for the Tropofolists are presented in Figures 7 to 10 along with data for two inorganic soils (Figure 11). The vertical axis indicates the amount of phosphorus in micrograms adsorbed per gram of soil. The horizontal axis corresponds to the amount of phosphorus in the soil solution in parts per million (ppm). A concentration of 0.1 ppm P in the soil solution is adequate to provide the phosphorus needs of most crops. The curves in Figure 11 show that a large quantity of P must be applied[1] (approximately equal to the quantity

[1]The quantity of P required in pounds per acre to attain a given concentration is numerically equal to twice the P adsorbed in µg/g.

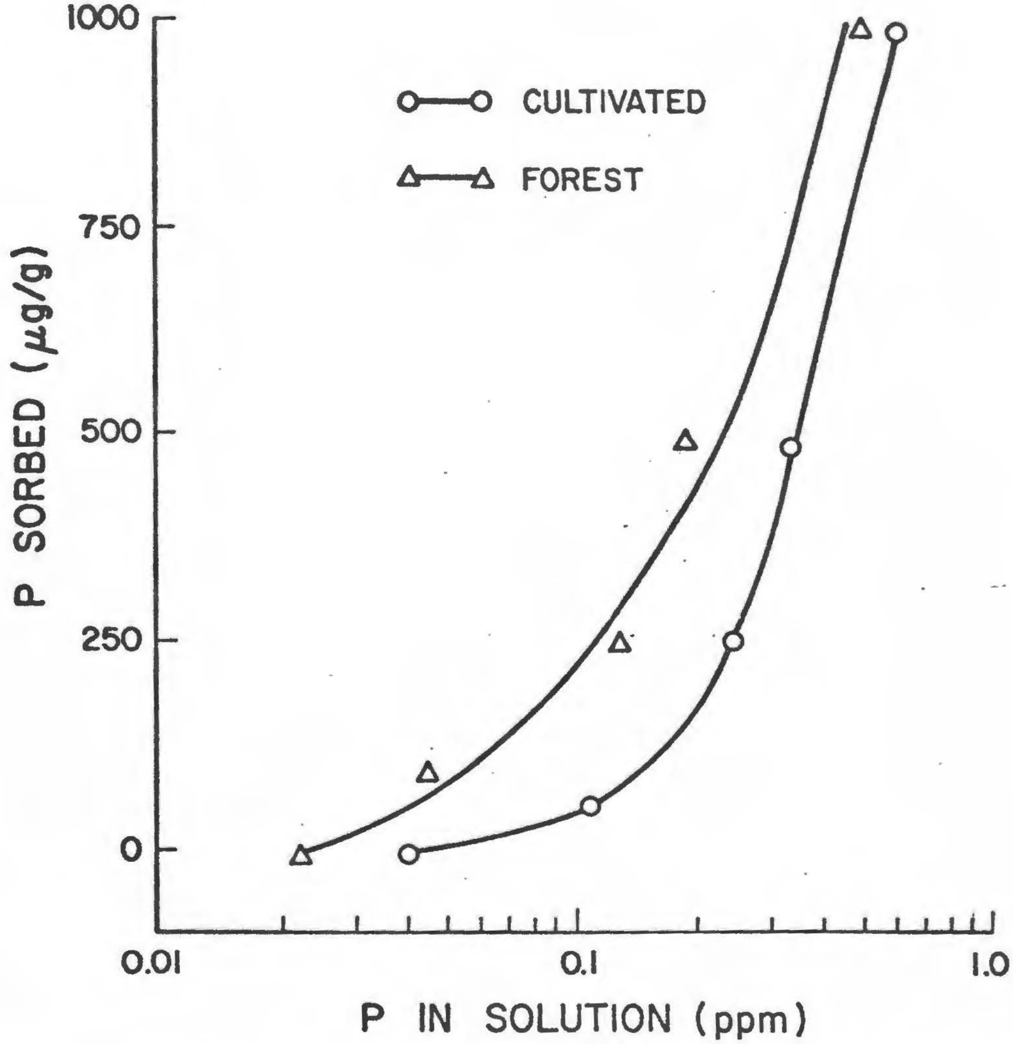

Figure 7. Phosphate sorption curves of the less than 2 mm size soil fraction from Keaau macadamia orchard and adjacent forest.

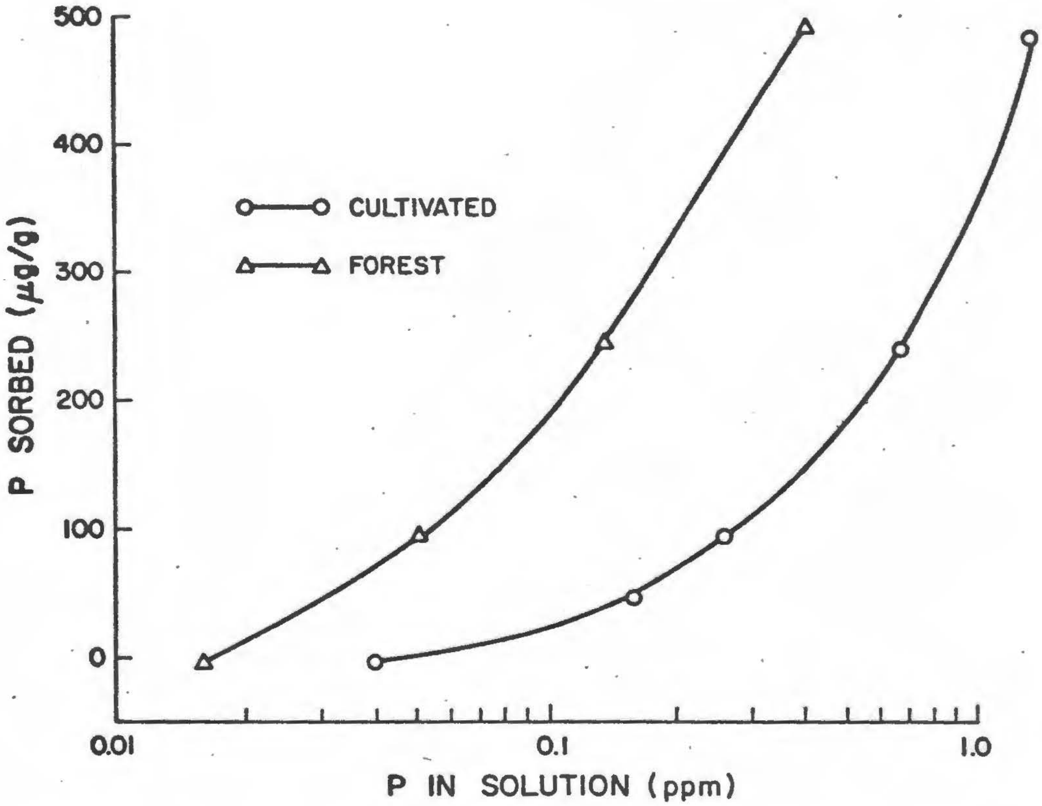

Figure 8. Phosphate sorption curves of the less than 2 mm size soil fraction from Honomalino macadamia orchard and adjacent forest.

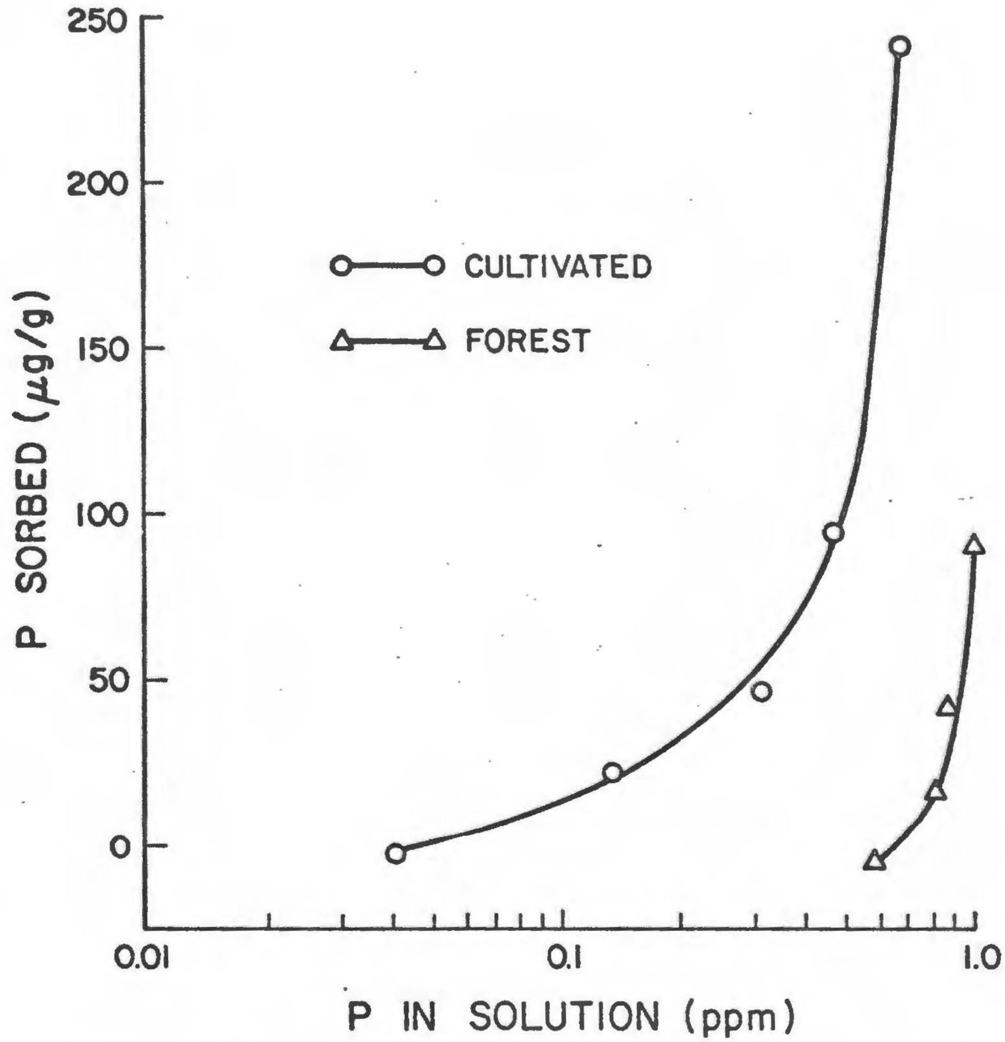

Figure 9. Phosphate sorption curves of the less than 2 mm size soil fraction from a Kalapana macadamia orchard and adjacent forest.

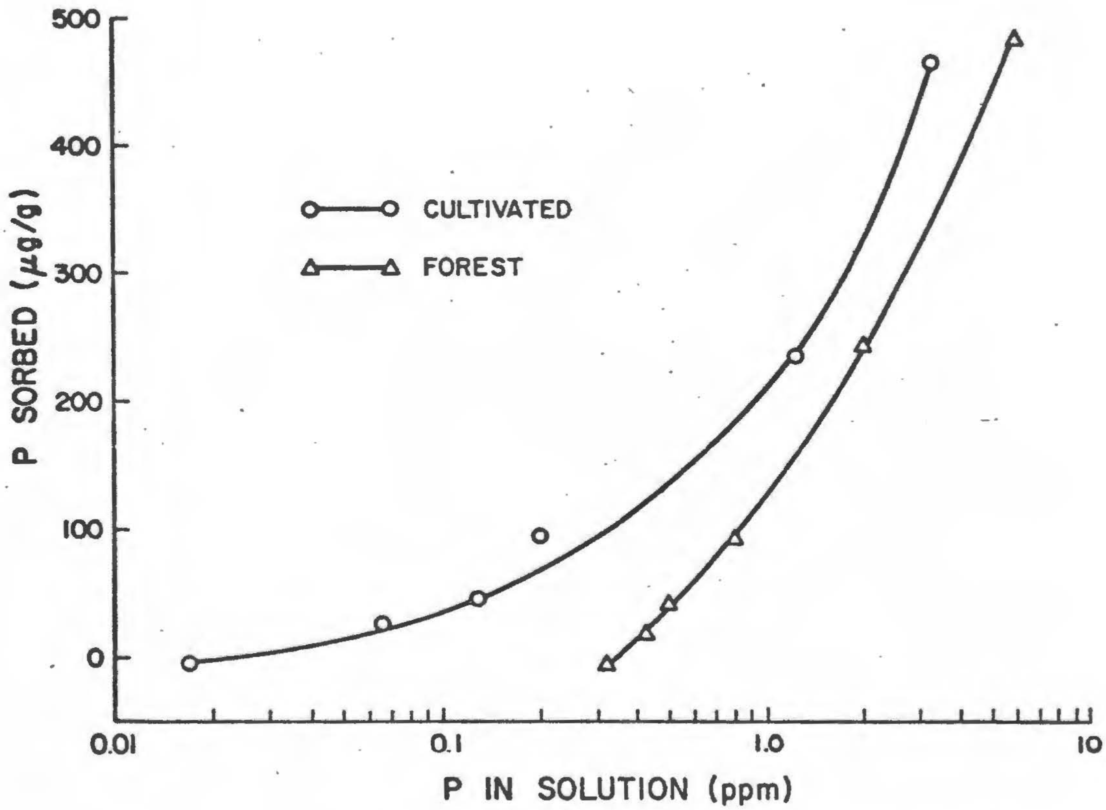

Figure 10. Phosphate sorption curves of the less than 2 mm size soil fraction from Malama-Ki Research Station cultivated area and adjacent forest.

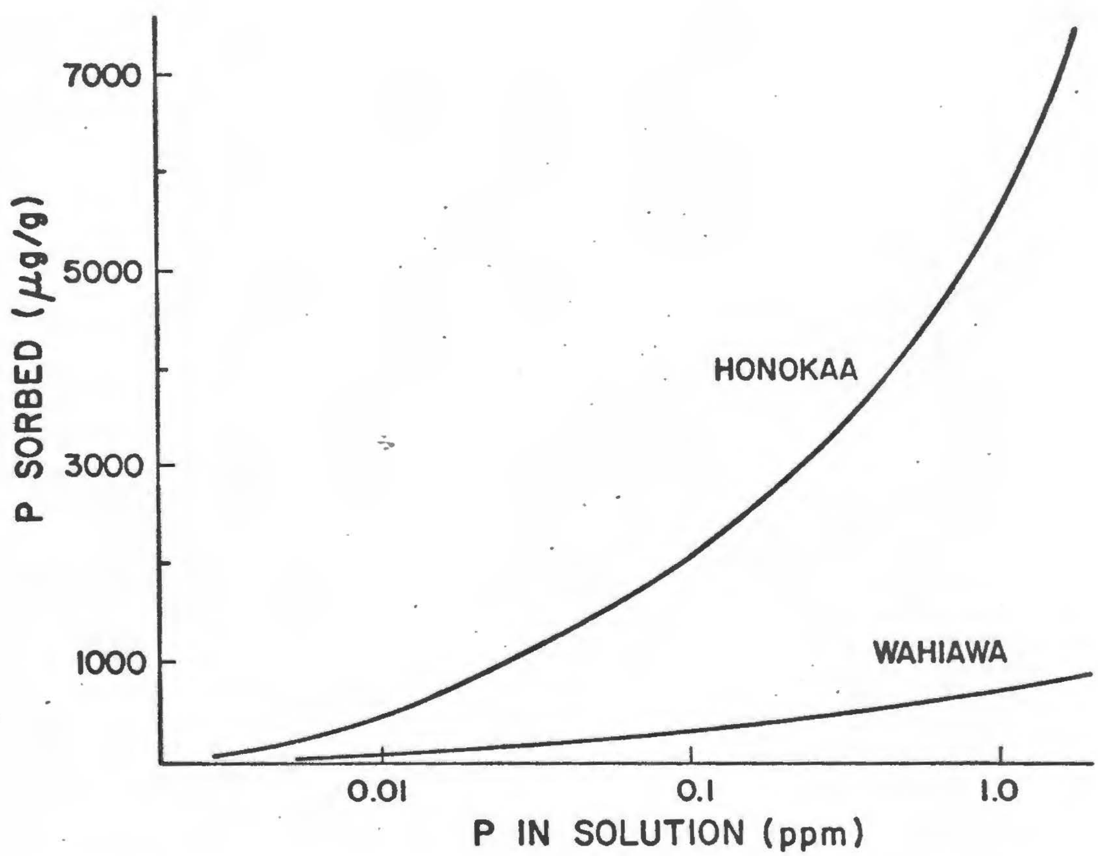

Figure 11. Phosphate sorption curves of the less than 2 mm soil fraction of Honokaa and Wahiawa series (Fox et al., 1972).

adsorbed) to the inorganic soils before this concentration is reached. Far less P needs to be applied to the fine fraction of Tropofolists to attain this concentration. Furthermore only a small fraction of Tropofolist is organic; most of the remaining mass is in large boulders with little or no capacity to adsorb P.

Table 7 gives a comparative amount of P which must be applied to Tropofolists and inorganic soils to attain 0.1 ppm P to a depth of 15 cm (6 inches). The computed values suggest that 10 kg of P per hectare (approximately 10 pounds per acre) will raise the P concentration in the soil solution to 0.1 ppm.

Current recommended practice (Yee et al., 1972) for papaya production is to apply this amount once a month.

In inorganic clay soils of Hawaii, the reservoir of adsorbed P would continue to supply the soil solution with P at adequate levels for several years. This obviously does not occur in Tropofolists.

The long term effect of heavy P application cannot be evaluated on papaya. A form of shifting agriculture, necessitated by plant disease, is practiced. In macadamia heavy application of phosphorus appears to be related to iron chlorosis (Fox et al., 1971; Jones et al., 1972).

In any case, the need for heavy application of fertilizers at frequent intervals suggests that only a small fraction of the applied P is retained by the soil. The remainder probably falls between the crevices or is leached beyond the root zone.

Table 7. Phosphorus Requirement of Soils to Raise Soil Solution P Level to 0.1 ppm

Soil Name	μg P Required to Bring Soil Solution Concentration to 0.1 ppm	Kg/Hectare of Less Than 2 mm Soil Material Surface in 15 cm Depth	Kg P Required to Raise Soil Solution Concentration to 0.1 ppm to a Depth of 15 cm
Keaau	40	202,500	8.1
Honomalino	25	277,500	7.0
Malama-Ki	45	94,500	4.3
Kalapana	15	133,500	2.0
Wahiawa	300	1,650,000	495.0
Honokaa	2050	630,000	1,291.0

Soil-Water Relations

Hydrology of Tropofolists That Are Not Cultivated

Hydrologically Tropofolists can be pictured as a two layer system consistent of a 5 to 15 cm (2-6 inches) mat of organic matter underlain by either a slab of pahoehoe lava or clinkers of aa lava. Drainage of water from the organic layer is partly restricted in both cases.

In the pahoehoe system the lava slab is impervious to water, and water must move laterally until it intercepts a fracture in the lava. Free water will drain through these fractures, but water held under tension in the organic matter will not. If the pahoehoe is relatively free of fractures, water will accumulate in localized areas after heavy rains. Because of the shallowness of the organic mat, these same areas can become very dry during summer months.

When the organic matter is underlain by aa lava, free water will drain, but water under tension in the organic layer will not. This occurs because the coarse clinker and boulders cannot draw water from the organic layer. This is analogous to water which will perch in a fine textured material underlain by gravel.

Hydrology of Cultivated Tropofolists

Land Clearing and Preparation

The surface of an aa field is rough and uneven. Even in level parts of the flow, the difference in elevation between adjacent high and low points range from 1 to 2 meters (3-6 feet). This micro-relief (see Figure 12) is preserved in the Tropofolists and the land is generally levelled after the area is cleared. Clearing and land

Figure 12. Example of tree burning and uneven topography.

preparation involves (1) felling of trees, (2) burning, (3) levelling and rolling. Figure 12 shows burning of felled trees in a freshly cleared forest, and Figure 13 shows equipment used for land levelling. A close up of levelled land is illustrated in Figure 14. Keller and Fukunaga (1968) give a cost breakdown for land clearing and preparation. They cite a cost of $250 per acre, but this amount is probably too low for current use.

For annuals the land must be prepared before each planting. This is commonly done by dragging a steel track from an abandoned tractor or large chains over the field. This operation removes weeds, and over several years, reduces the size of the rock fragments. No tillage is needed since soil compaction in the conventional sense does not occur in these soils. A field reserved for a corn breeding experiment on the Waiakea Research Station has been prepared in this manner for several years.

Effect of Land Clearing on Hydrology

During the land clearing operations much of the organic material is buried. The organic matter no longer occurs as a continuous surface layer but is scattered in isolated pockets throughout the profile. These pockets act as sponges and hold water against gravity if they are surrounded by coarse clinkers. Furthermore these pockets are less likely to lose water by evaporation. In most cleared and cultivated lava soils, organic matter has filtered below the surface, and the field appears totally free of organic matter (see Figure 15). For purposes of water and nutrient retention, the usefulness of organic matter is enhanced by its incorporation into the subsoil.

Figure 13. Levelling operations.

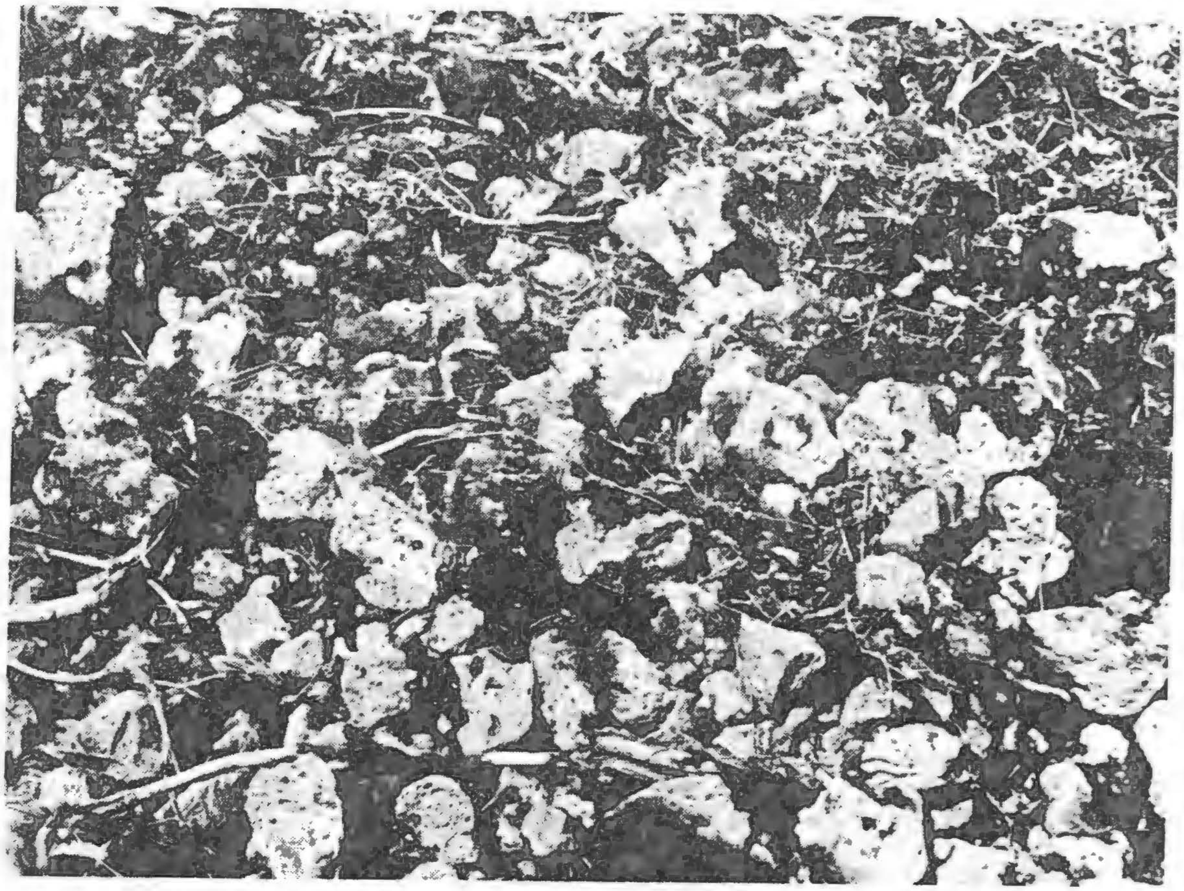

Figure 14. Close-up of levelled land surface exhibiting freshly fractured face of rocks up to about 12 cm diameter.

Figure 15. Guava orchard floor devoid of organic layer.

In roads frequently used by wheeled vehicles, closer packing of the lava fragments and subsequent sealing of the pores by finely divided organic matter sometimes cause water to accumulate on the surface.

Soil-Water Measurement

There are well established methods for measuring, computing and expressing water holding capacities of homogenous soils. Water content can be expressed on a weight (gravimetric) or volume bases. On a weight basis water content is expressed as grams water retained by one gram of dry soil (g/g). On a volume basis water content is expressed as gram water retained in one cubic centimeter of soil g/cm^3. The relation between gravimetric water content Θ_g, and volumetric water content Θv is expressed by:

$$\Theta v = \rho \, \Theta_g$$

where ρ is the bulk density. The more useful parameter is the volumetric water content, for this value when multiplied by depth gives the water content stored in a soil in inches or centimeters.

Unfortunately this simple approach for describing soil water is not suited to Tropofolists. A soil consisting mainly of large rocks interspersed with pockets of organic matter wedged in crevices and joints does not lend itself to easy measurement of soil water. And yet it is helpful to know the volume of water retained in a given volume of soil (water storage capacity) and to estimate the number of days this supply will last for several rates of consumptive use by crops.

Water-Retention of Less Than 2 mm Size Fraction

As a first approximation it is assumed that pores between particle greater than 2 mm in diameter do not contribute to water retention. Thus while the soil possesses large pores between boulders, these pores do not serve as reservoir for water storage.

The first task is to measure the organic matter content in a given volume. The second task is to obtain an average bulk density of the <2 mm sized fraction which occurs as pockets between large boulders, and finally it is necessary to obtain a moisture release curve of this organic material. Yaibuathes (1971) has measured bulk densities for a number of samples from Tropofolists. Analysis of Yaibuathes' data show that there is a significant regression between organic matter content and bulk density, as shown in Figure 16. The equation which relates bulk density to organic matter is:

$$\rho = a + b\ (\mathrm{O.M.})$$

where ρ is the bulk density, O.M. is organic matter and a and b are constants. Yaibuathes has also measured water content-suction curves for samples with measured bulk density.

Based on the relationships in Figures 16 and 17 one can compute the quantity of water held in a given depth of soil at any tension between zero and 15 bar suction. The only information necessary to make this computation is the organic carbon or organic matter. The organic carbon contents are provided in Table 3. Water retention by the less than 2 mm soil fractions are presented in Table 8. Water retained in a soil attributable to organic matter ranged from practically zero to as high as 4.6 mm/cm in the horizons examined.

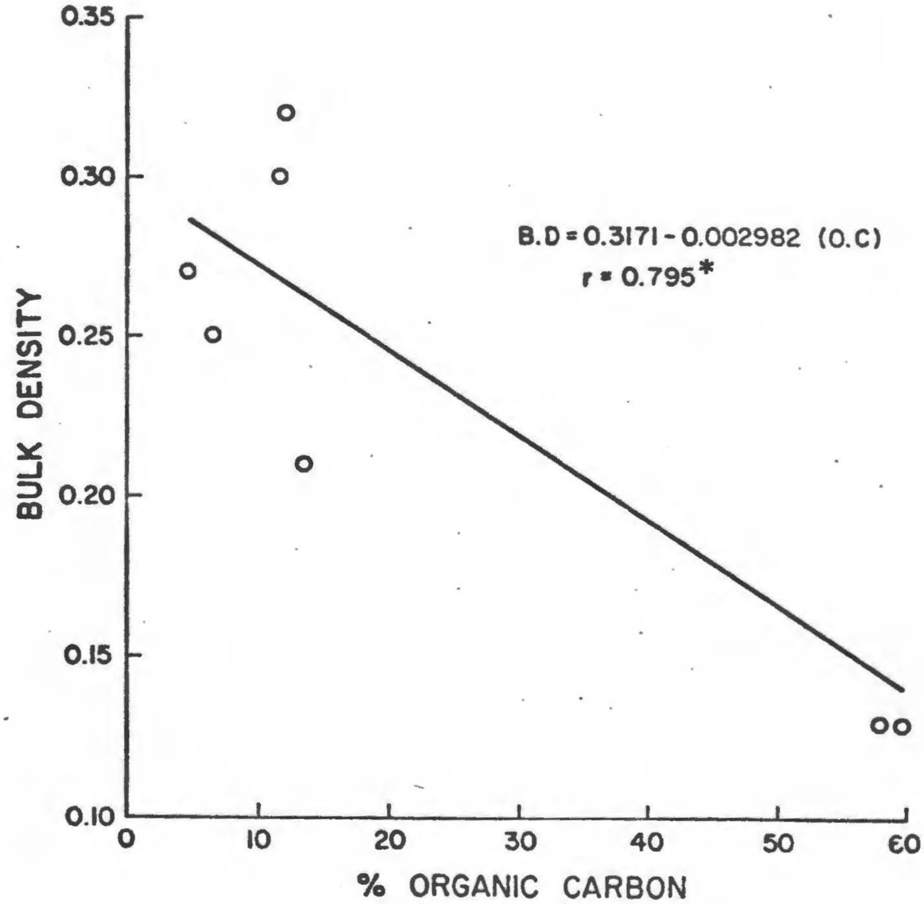

Figure 16. Regression of bulk density on organic carbon.

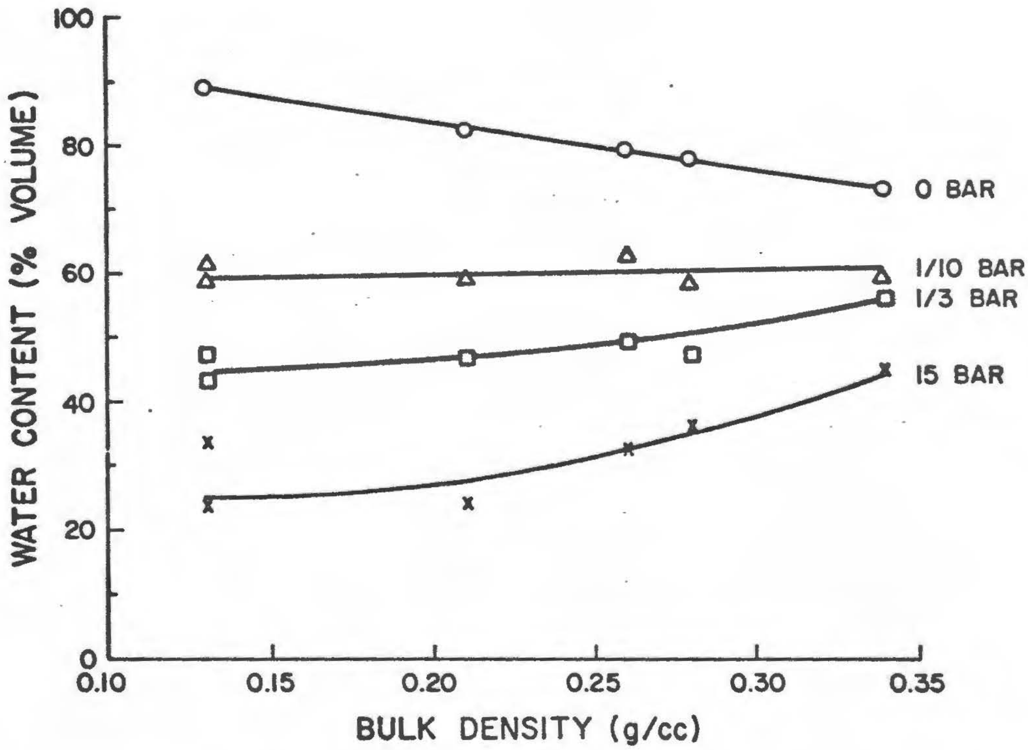

Figure 17. Water contents of the less than 2 mm size soil fraction from typic Tropofolists as a function of soil moisture tension (bars) and bulk density.

Water-Retention of Clinkers (2-6 mm, 6-12.5 mm)

In computing the water retention capacity of Tropofolists, it was assumed, as a first approximation, that all of the water was held by organic matter. The lush vegetative growth on Tropofolists and even on relatively fresh lava flows suggests that aa rocks can hold some water against the forces of gravity.

A simple experiment was conducted to measure the volumes of water retained by aa clinker as a function of applied suction. Aa clinkers washed free of organic matter were placed in a cylindrical container and immersed in water and subsequently allowed to drain. Greater suction was imposed on the clinkers by placing the container on quartz sand equilibrated with an adjustable water table.

The relationship between volumetric water content of clinker and suction is illustrated in Figure 18.

The relationship between the mass of clinkers to volume of the cylindrical container of the above experiment was used to determine the volume of clinkers in each horizon. The relation of volumetric water content of clinkers to suction of 10 cm was used to estimate the water retention by clinkers and values are presented in Table 8.

Even for clinker with diameter ranging from 6 to 12.5 mm, the volume of water retained is not small. The fact that there is little change in water content beyond 10 cm tension suggests that the water is perched in micro-depressions in the upper face of the clinker. This is possible in irregularly shaped clinkers but not possible in water-worked pebbles or sand with smooth, rounded surfaces. The often made statement that "aa soils" have low water holding capacity is still correct but should be made with the above fact in mind.

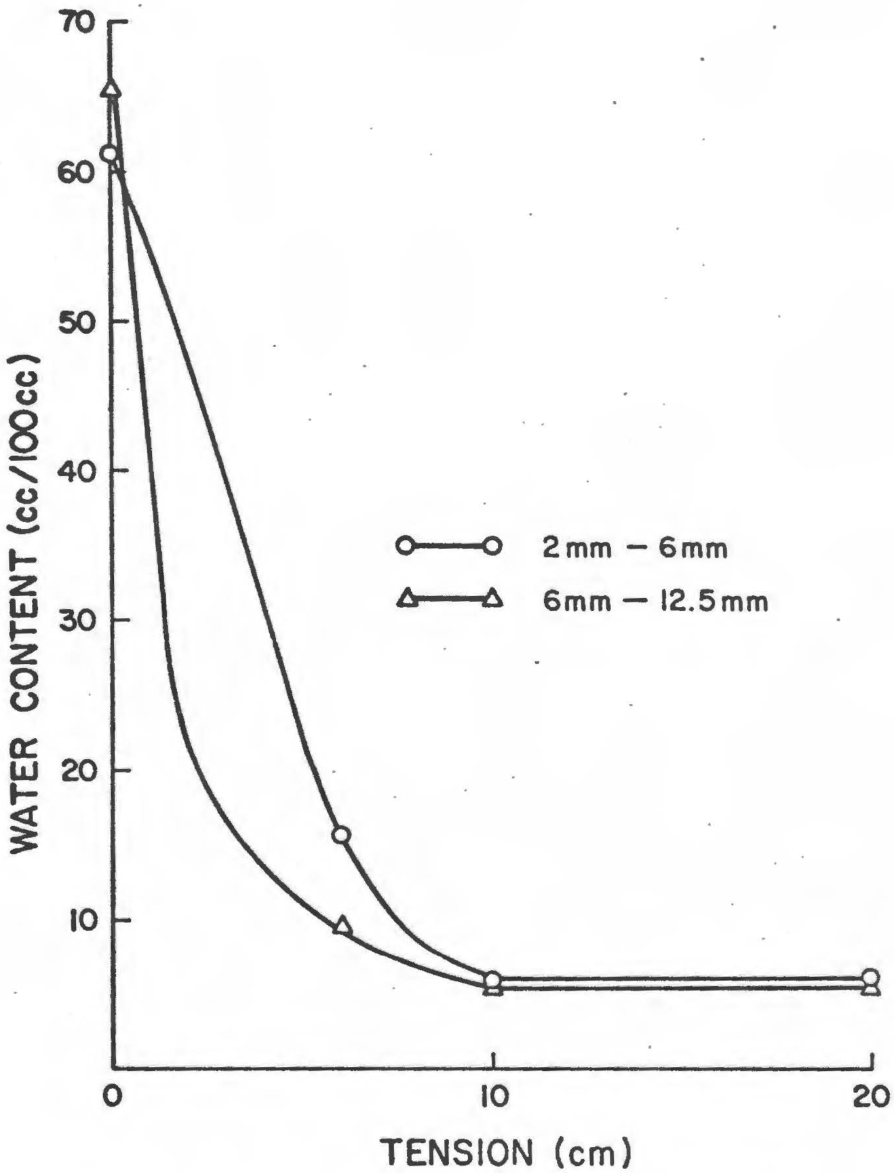

Figure 18. Water retention of cinders 2-6 mm and 6-12.5 mm size under different tensions.

Table 8. Water Retained by Soil Materials Collected as a Function of Depth. Water Content in Each Horizon is Expressed in mm/cm[a]

Sample Location	Profile No.	Depth cm	Water Retained by <2 mm mm/cm	Water Retained by 2-6 mm mm/cm	Water Retained by 6-12.5 mm mm/cm	Total Water Held mm/cm
Honomalino						
Low elevation						
Cultivated	1	0-5	3.238	0.040	0.024	3.30
		5-13	1.588	0.013	0.015	1.62
		13-25	0.632	0.005	0.005	0.64
"	2	0-5	1.068	0.024	0.026	1.12
Forest	1	0-13	1.280	0.034	0.010	1.32
"	2	0-15	2.114	0.007	0.008	2.13
Medium elevation						
Cultivated	1	0-8	1.482	0.015	0.019	1.89
		8-18	1.182	0.026	0.005	1.21
		18-51	0.846	0.007	0.016	0.87
"	2	0-8	1.017	0.017	0.036	1.07
		8-25	1.164	0.017	0.002	1.20
		25-51	0.830	0.021	0.042	0.89
"	3	0-15	2.402	0.013	0.026	2.43
		15-30	2.085	0.038	0.051	2.17
		30-36	0.506	0.056	0.120	0.68
"	4	0-8	1.738	0.030	0.067	1.84
		8-20	0.269	0.056	0.115	0.44
		20-38	0.436	0.030	0.053	0.52
"	5	0-3	-	-	-	-
		3-10	1.284	0.054	0.090	1.43
		10-25	0.626	0.016	0.030	0.67
		25-41	0.253	0.005	0.008	0.27
"	6	0-3	-	-	-	-
		3-20	0.541	0.011	0.034	0.59
		20-38	0.536	0.007	0.025	0.57

Table 8. (Continued) Water Retained by Soil Materials Collected as a Function of Depth. Water Content in Each Horizon is Expressed in mm/cm[a]

Sample Location	Profile No.	Depth cm	Water Retained by <2 mm mm/cm	2-6 mm mm/cm	6-12.5 mm mm/cm	Total Water Held mm/cm
Forest	1	0-8	1.631	0.002	0.008	1.64
		8-13	1.786	0.006	0.006	1.80
"	2	0-8	2.188	0.007	0.001	2.20
		8-13	4.588	0.004	0.004	4.60
High elevation						
Cultivated	1	0-5	3.888	0.048	0.068	3.50
		5-13	0.262	0.003	0.007	0.27
"	2	0-8	1.316	0.002	0.007	1.33
		8-20	1.216	0.005	0.006	1.23
		20-30	0.933	0.009	0.013	0.96
"	3	0-8	1.038	0.018	0.025	1.08
Forest	1	0-8	3.526	0.005	0.006	3.54
		8-15	1.024	0.012	0.037	1.07
"	2	0-15	2.232	0.004	0.003	3.24
		15-23	0.748	0.001	0.001	0.75
<u>Keaau</u>						
Cultivated	1	0-10	1.250	0.073	0.074	1.40
		10-20	0.789	0.051	0.094	0.93
		20-30	1.724	0.053	0.063	1.84
		30-46	1.016	0.030	0.038	1.08
"	2	0-15	0.227	0.010	0.013	0.25
		15-30	0.444	0.014	0.012	0.47
		30-46	0.378	0.013	0.012	0.40
"	3	0-15	1.018	0.037	0.034	1.09
		15-31	0.931	0.020	0.030	0.96
		31-51	0.574	0.011	0.017	0.60
Forest	1	0-10	0.651	0.009	0.022	0.68
		10-20	0.639	0.010	0.019	0.67
		20-33	1.022	0.010	0.023	1.06
		33-46	0.474	0.009	0.016	0.50

Table 8. (Continued) Water Retained by Soil Materials Collected as a Function of Depth. Water Content in Each Horizon is Expressed in mm/cm[a]

Sample Location	Profile No.	Depth cm	Water Retained by			Total Water Held mm/cm
			<2 mm mm/cm	2-6 mm mm/cm	6-12.5 mm mm/cm	
Cultivated	4	0-15	1.286	0.073	0.047	1.41
		15-30	0.670	0.026	0.020	0.72
		30-46	0.558	0.021	0.016	0.53
"	5	0-15	0.972	0.007	0.053	1.10
		15-30	0.576	0.060	0.053	0.69
		30-46	0.341	0.023	0.020	0.38
"	6	0-5	3.112	0.042	0.046	3.20
		5-20	0.467	0.037	0.046	0.55
		20-36	0.243	0.009	0.016	0.27
Cultivated	7	0-8	0.736	0.011	0.012	0.76
		8-18	0.438	0.012	0.019	0.47
		18-36	0.431	0.009	0.010	0.45
		36-51	0.114	0.002	0.002	0.12
"	8	0-5	5.502	0.094	0.048	4.64
		5-15	1.390	0.048	0.049	1.49
"	9	0-3	5.613	0.133	0.066	5.81
		3-20	1.205	0.031	0.040	1.28
Malama-Ki						
Cultivated	1	0-8	-	-	-	-
		8-20	0.470	0.062	0.045	0.58
		20-33	0.210	0.013	0.016	0.24
Forest	1	0-31	0.122	0.001	0.001	0.05
Kalapana						
Cultivated	1	0-15	0.913	0.030	0.058	1.00
		15-30	0.706	0.027	0.035	0.77
		30-45	0.396	0.020	0.020	0.44
"	2	0-45	0.129	0.005	0.001	0.15

[a]Water retention of less than 2 mm size fraction is calculated between tensions 1/10 and 15 bar, and for cinders of 2-6 mm and 6-12.5 mm a tension of 10 cm was used.

Water-Retention of Less Than 12.5 mm Size Fraction

The last column of Table 8 gives the water holding capacity in mm/cm for each depth increment. A value of 1 mm/cm is equivalent to a volumetric water content of 10% or 1.2 inches of water in one foot of soil. The average value for all depth is 1.24 mm/cm. If this quantity of water were available to a depth of one meter, there would be a total of 12.4 cm of water for plant use. This quantity of water would provide a 12 day supply if water were consumed at the rate of one centimeter per day. On the other hand organic matter content is appreciable only to a depth of about one-third meter and it is very likely that water retention below the depth is considerably smaller.

The data suggest that water holding capacity in itself is not as serious a limiting factor in Tropofolists as has been thought. There are two other factors which contribute to the droughtiness of Tropofolists. The first is uneven rainfall distribution. In the Kona district where rainfall is highest during the summer months when need for the water is greatest, sixty inches per year is adequate to support a crop of macadamia. In the Hilo-Puna area 100 inches of rain falling mostly in the winter months may not supply sufficient water during the hot summer months. A second factor may be the low rate of water transmission in the soil. A large isolated volume of fines rich in organic matter and well supplied with water and nutrients cannot serve as a source of water or nutrient if it is not intercepted by roots. In fine textured uniform soils, soil volume not occupied by roots still act as sources because water can move from that source to the roots.

If an irrigation system suitable for Tropofolists can be devised, large sections of areas not now under cultivation may yet be profitably developed for crop production.

Comparison of Water Retention in Forest and Cultivated Soils

The mean values of water retention of horizons from forests and cultivated sites were 1.58 and 1.14 mm/cm, respectively. Although the difference is large these means were not significantly different. It is difficult to show differences in means because of the wide variation in water retention values. The average sampling depth in forested sites was 25 cm, and for cultivated sites 35 cm. The higher mean water retention values for the forested sites is partly attributable to the fact that there are a larger proportion of surface samples collected from forest sites. In many forest sites it was only possible to collect the loose surface organic layer. Samples from cultivated sites included many which were low in organic matter content collected from greater depths. Samples were collected to greater depths in cultivated sites because it was physically possible to do so.

In any case it was not possible to show that land clearing and subsequent cultivation lowers the water holding capacity of Tropofolists. In fact there is a suggestion that redistribution of organic matter to lower horizons, fracturing of large boulders during land clearing, and close packing of the rock fragments during levelling all contribute to improvement in water retention of Tropofolists.

Factors Affecting Crop Production

Aa Versus Pahoehoe Tropofolists

Fresh lava flows can be readily categorized as aa or pahoehoe. Aa flows are comparatively loose and clinkery, whereas pahoehoe flows are smooth and billowy. This difference in rock texture has an important bearing on crop production. For this and other reasons Tropofolists are separated into Typic (aa) and Lithic (pahoehoe) subgroups. Under optimum rainfall and temperature situation, aa or Typic Tropofolists is better suited for crop production. About 43% of Tropofolists fall in the Typic subgroup.

Rainfall

In lower elevations, the major limiting factor for crop production on Tropofolists is water. In areas where rainfall is low, prehistoric lava flows appear as though they have erupted only recently. When annual rainfall exceeds 100 inches, historic lava flows less than 150 years old are forested and thus mapped as Tropofolists. The 1843 Mauna Loa aa flow, for example, is associated with at least three soil series depending on rainfall and elevation (temperature regime).

Because of the low water holding capacity of Tropofolists heavy and frequent rainfall are needed to support plant life. There is however a marked difference in crop performance for identical soils which occur in the Kona district relative to those in the windward side of the island. In Kona, a 60 to 90 inch rainfall between 0 and 1000 feet elevation on aa land is adequate to support most tree crops, but on the windward side this range of rainfall is marginal for the same crops. This difference arises because the rainfall maxima comes in the summer months in Kona, when the water requirement is greatest. In addition, low wind velocity in the Kona district also results in lower consumptive use of water by crops.

The classification system in its current form does not take this difference into account. Since the criterion for separation of soils at the series level is rainfall, future revisions of the classification scheme for Tropofolists need to separate soils on the same lava type, soil acidity, temperature regime and rainfall into those with rainfall maxima in winter and those with rainfall maxima in summer. The observation to date suggests that the 40 to 60 inch rainfall range in Kona is equivalent to the 60 to 90 inch range in the Puna-Hilo area. Similarly, the 60 to 90 inch rainfall in Kona is as effective as the 90 to 150 inch rainfall range in the Puna-Hilo area. When rainfall exceeds 150 inches annually, this criterion for soil separation becomes less important.

Soil Temperature

At the higher elevations low soil and air temperatures and possibly excessive cloud cover become the limiting factor for crop production. Papaya, a major crop, grown on Tropofolist appears to do best at elevation below 500 feet. Macadamia nut yields begin to decrease sharply at about 1800 feet elevation and economic yields are generally not possible beyond 2500 feet.

Soils are separated at the family level on the basis of soil temperature. Soil temperature is generally not a limiting factor below 1000 feet elevation. All soils which occur below this elevation are placed in the isohyperthermic family and have a mean annual soil temperature greater than 22° C (72° F).

Soils which occur between 1000 feet and 3500 feet are placed in isothermic families 15° C (59° F). This temperature range seems to present some problems. Some crops which do well in the 1000 to 1500 feet may not do well in the 1500 to 3500 feet elevation and yet a soil series may occur from 1000 to 3500 feet. The prominent series which falls in this category is the Kiloa, a member of the dysic isothermic family of the Typic Tropofolist, which falls in the 90 to greater than 150 inch rainfall belt. The Kiloa series covers 63,000 acres.

It may be useful to include in the classification scheme some means to accommodate this wide range in land use potential in the isothermic family. For crops currently grown on Tropofolists, 2000 feet appear to be the practical upper limit for economic production.

Organic soils are "cold" soils; the amplitude of the diurnal temperature fluctuation decreases very rapidly with depth. In other words the penetration of heat into wet organic matter is low in comparison to most inorganic soils. Below the organic mat, large air gaps, small contact area between rocks, the high heat capacity of the rock all add to the difficulty of warming the soil.

In cleared land, redistribution of the organic layer below the surface allows the exposed rocks to absorb heat. The redistributed organic matter continues to serve as an insulater in the subsoil, thereby reducing the efficiency of heat transfer in the subsoil.

It is probable that soil temperature becomes a critical limiting factor more quickly in Tropofolists than in other soils of the State.

Soil Acidity

Tropofolists are separated into euic and dysic families on the basis of soil acidity. Euic families have soil pH values greater than 4.5 in 0.1 M $CaCl_2$, while the dysic families have values less than 4.5. Separation of soil on the basis of soil acidity appears to be less useful than other criteria used to categorize Tropofolists. The texture of the underlying lava, rainfall and soil temperature are the essential parameters which determine potential of a particular soil series for crop production.

There are more dysic families in the pahoehoe (Lithic) than in the Typic (aa) Tropofolists. Organic matter is acidic in character but upon intimate mixing with the fine clinkers, neutralization of acid groups with calcium, magnesium and sodium ions tend to raise the pH in Typic Tropofolists.

Euic families are also more common in the low rainfall belt because of less intense leaching. One exception to this is the Malama series which occurs on aa lava in the 60 to 90 inch rainfall belt below 1000 feet elevation but yet falls in the dysic family. Data collected by Yaibuathes (1971) and in this study (see Table 3), however, show that the Malama more correctly belongs in the euic family. This discrepancy, however, is not serious because the euic-dysic distinction is a relatively unimportant criterion for crop production in these soils.

Agricultural Potential of Tropofolists

Low Elevation Tropofolists

Typic Tropofolists

Intensive agricultural use of Tropofolist is largely confined to the Typic (aa) subgroup which occur at elevation below 2000 feet and where rainfall is high. In the windward zone (Puna-Hilo district) rainfall must be greater than 90 inches before the land can be cropped. In the leeward side of the island (Kona) where the rainfall maximum appears during the summer months and evapotranspiration is lower, an annual rainfall of 60 inches is equivalent to or more effective than 90 inches in the windward zone. Because this climatological difference has a pronounced influence on land use, the soil in the windward zone is discussed separately from those which occur in the area with summer rainfall maxima.

Zone of Winter Rainfall Maxima. On the windward side of the island, the Papai series, which occurs below 1000 feet and in areas with rainfall greater than 90 inches, is the most important series. Based on current estimate, there are approximately 21,000 acres of this series. Papaya and macadamia are grown on this soil. However, in the wetter range of this series papaya culture is prevented by high incidence of disease. This is well illustrated by the number of papaya research projects conducted on the Waiakea and Malama-Ki Research Stations of the Hawaii Agricultural Experiment Station. Both stations are located on soils which meet the criteria of the Papai series but the Malama-Ki Station occurs in the drier range while the Waiakea Station occurs in the wetter range of the series. Papaya research is largely confined to the Malama-Ki Station because the environment is better suited for this crop. The factor which restricts papaya culture at the Waiakea Station is the high incidence of plant disease associated with high rainfall. The relevant soil and climatological data for both stations are provided in Table 9.

There is no indication of limitation for macadamia nut production in the full range of this soil.

The Malama series differs from the Papai in annual rainfall. Annual rainfall for the Malama is 60 to 90 inches which is marginal for most crops. While 60 to 90 inches rainfall is adequate when properly distributed, too often, dry summer months cause serious damage to crops. A minimum of 10 inches per month of rain during the summer months is required to sustain a papaya crop[2].

There are approximately 12,500 acres of the Malama series in the Puna district. This soil has a high agricultural potential if a suitable irrigation system can be developed for Tropofolists.

The Kiloa series occurs at elevation above 1000 feet and lies in juxtaposition to the Papai series in the Hilo-Puna district. Rainfall is higher and the temperature is cooler in the Kiloa series. The agricultural potential of this soil is not as great as in the Papai series but citrus and macadamia may be produced below the 2000 feet elevation.

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[2]Personal communication with Mr. M. Awada, Associate Plant Physiologist, Hawaii Agricultural Experiment Station (1972).

Table 9. Soil and Climatological Data on Waiakea and Malama-Ki Experiment Stations[a]

Station	Elevation (feet)	Average Maximum Temperature °F	Average Minimum Temperature °F	Annual Rainfall (inches)
Waiakea	525	79	63	183
Malama-Ki	250	80	67	127[b]

[a]Data obtained from the Office of the Associate Director, Hawaii Agricultural Experiment Station (1971).

[b]The Malama-Ki Station is currently surveyed as the Malama series. The recorded rainfall and new data on soil pH place this area into the Papai series.

Zone of Summer Rainfall Maxima. The Kona district and portions of the Ka'u district east of the line connecting the summit of Mauna Loa with South Point have summer rainfall maximum. The important Typic Tropofolists in this area are the Kaimu, Puna and Kiloa series.

Although the Puna series can occur at elevations ranging from 1000 to 3500 feet, this soil is largely confined to the 1000 to 2000 feet elevation in this region. This narrow belt constitutes the area of highest agricultural potential in Kona-Ka'u district. Macadamia, coffee, citrus production and ranching have been successfully carried out on this soil. There are 25,000 acres of Puna series, mainly concentrated in the Kona district between the 1000 and 2000 feet elevation belt.

The Kaimu series occurs below and parallel to the Puna series at an elevation less than 1000 feet. The Kaimu series in the Kona district has agricultural potential similar to that of the Malama series of the windward zone even though the rainfall is 40 to 60 in the Kaimu and 60 to 90 inches in the Malama.

Running parallel to and just above the Puna series, a belt of higher rainfall zone is mapped as the Kiloa series. Although the Kiloa can occur at an elevation as low as 1000 feet, it generally begins at the 2000 feet elevation in the Kona district. Crops do not do well beyond 2000 feet, and the Kiloa is not used extensively for crop production.

Summary of Agricultural Potential of Typic Tropofolists. The Papai and Puna series, and in addition the wetter parts of the Kaimu and Malama series and the Kiloa at lower elevations, represent the Typic Tropofolists which meet the rainfall and temperature requirements for crop production. Areas of high agricultural potential include all of the areas mapped as Papai and Puna series and approximately 10% of the areas mapped as Kaimu, Malama or Kiloa series. Table 10 gives an estimate of this area.

Lithic Tropofolists

Zone of Winter Rainfall Maxima. The Lithic counterpart of the Papai series is the Keaukaha series with 24,500 acres. The Opihikao series covering 10,000 acres occurs in association with the Malama series, but is less suitable for crop production because of the underlying pahoehoe rock.

Some indication of the agricultural potential of the Keaukaha can be obtained from its use at the Waiakea Research Station. Experimental plantings of macadamia (see Figure 19) and guava on the Keaukaha and Papai soils show no apparent differences in tree growth. On the other hand, there is no crop planted in the Keaukaha soil at the Malama-Ki Station. It appears that while the Papai can support crops at both stations, the Keaukaha can do so only at the Waiakea Station where rainfall is higher (see Table 9). This suggests that all things being equal a higher rainfall is required to support crops on Lithic than on Typic Tropofolists.

The Lithic Tropofolists which occur below 2000 feet elevation in areas of rainfall greater than 150 inches need further studies because of their undetermined agricultural potential.

Table 10. Estimate of Potentially Usable Land Area of Typic Tropofolists in Hawaii

Soil Series	Total Acreage	Usable Area	
		Percent	Acres
Papai	21,000	100	21,000
Puna	25,000	100	25,000
Malama	12,500	10	1,250
Kaimu	19,000	10	1,900
Kiloa	63,500	10	6,350
Total			55,500

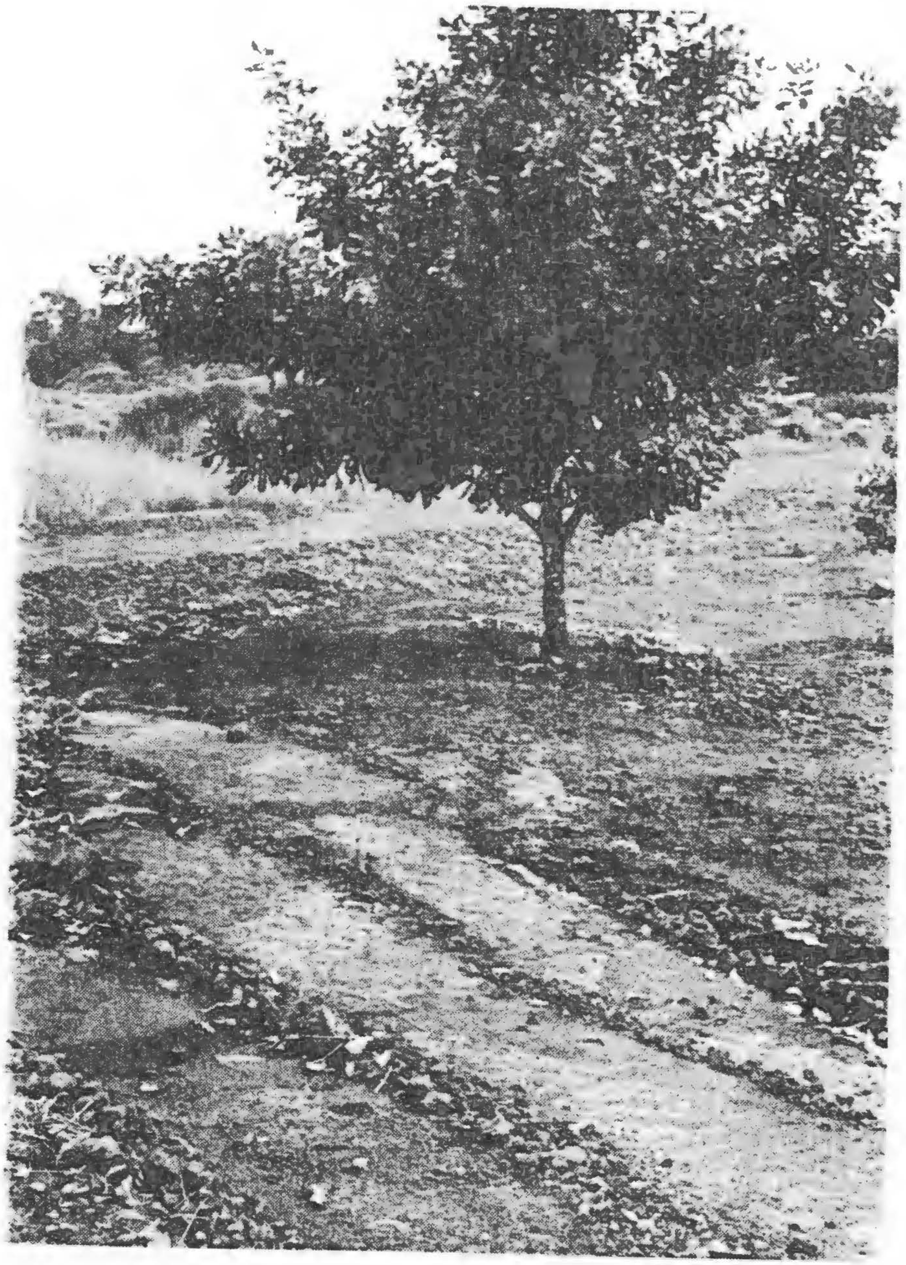

Figure 19. Macadamia growing on pahoehoe lava.

Zone of Summer Rainfall Maxima. In the leeward Kona district, the Punaluu and Kona series are the lithic counterparts of the Kaimu and Puna series, respectively. Here, crop production, if it occurs, would most likely be confined to the Kona series which occur between the 1000 and 2000 feet elevation where rainfall is greater than 100 inches. No survey of crop production of the Kona series was available and the potential of this soil for crop production is presently unknown.

Summary of Agricultural Potential of Lithic Tropofolists. The agricultural potential of the Lithic Tropofolists is largely untested. All things being equal a higher rainfall is required to support crops on Lithic than on Typic Tropofolists. The best estimate is that 150 and 100 inches annual rainfall are needed to support crops in the windward and leeward zone, respectively.

Only a rough estimate of the acreages of Tropofolists in the Lithic subgroup, which can be used for crop production, can be made at this time. If future research and experience bear out the limited research results obtained on the Keaukaha series at the Waiakea Research Station, the Lithic Tropofolists may eventually prove to be a major future soil resource for the State.

A conservative estimate of the potentially usable land in the Lithic Tropofolists are given in Table 11. With supplementary irrigation this area can be doubled.

Table 11. Estimate of Potentially Usable Land Area of Lithic Tropofolists in Hawaii

Soil Series	Total Acreage	Usable Percent	Area Acres
Keaukaha	24,500	25	6,125
Kona	25,500	25	6,375
Total			12,500

High Elevation Tropofolists

Potential for crop production on Tropofolists is in most cases restricted to elevation below 2000 feet. The soils which occur at elevation greater than 2000 feet are approximately 60% of the isothermic families and all of the members of the isomesic families. The high elevation soils, not generally suited for crop production constitute 60% of the Tropofolists or 278,000 acres.

Soils of the isomesic families include the Mawae and Lalaau of the Typic subgroup and the Kekake and Kahaluu of the Lithic subgroup. They have little or no potential for agriculture. They cover 157,000 acres and occur between the 3500 and 7000 feet elevation belt.

Sixty percent or 121,000 acres of the isothermic families occur between the 2000 and 3500 feet elevation. This area has some potential for some crops. Christmas tree (Norfolk Island Pine) will grow in this region as well as at lower elevations, but whenever possible this crop should be produced at the higher elevation to reserve the lower elevations for crops which require warmer climate.

The 2000 to 3500 feet elevation belt also has potential for pasture. Two major forage grasses, pangola and kikuyu, do well up to 3500 feet. The problem of winter forage production however would be more serious at these elevations than in the isohyperthermic soil families.

As in other crops, pasture may perform better on Typic than on Lithic Tropofolists, but there is no documented evidence to support this contention.

Recommendations

1. A major factor which restricts assessment of the agricultural potential of Tropofolist is the lack of a detailed soil survey. A detailed soil survey of the areas with high agricultural potential is urgently needed. The high potential areas include soils currently mapped as Papai and Puna series. A more detailed delineation of the boundaries between aa and pahoehoe Tropofolists will assist agriculturists to identify areas with immediate high use potential.

Areas mapped as Malama and Kaimu series should be the second group to receive close scrutiny.

2. Research to develop an irrigation system suitable for Tropofolist is needed. The Malama and Kaimu series which have marginal value for crop production can be put to intensive crop production with irrigation.

3. Research to ascertain the potential of Lithic (pahoehoe) Tropofolists is needed. This research should concentrate on developing management systems which will permit full utilization of

forested pahoehoe lands. The Keaukaha series would be an ideal test soil for this research. Approximately 57% of Tropofolists fall in the Lithic subgroup.

4. The following changes in the classification scheme for the Tropofolists will enhance the value of classification for predicting soil behavior.

a. Deletion of the euic or dysic distinctions.

b. Changing the range for isothermic temperature regimes from 57-72° F to 67-72° F. The current temperature range is too large to be useful.

c. Soils which occur in areas with summer rainfall maximum such as in Kona should be separately classified from those which occur in areas with winter rainfall maximum.

SUMMARY AND CONCLUSIONS

Tropofolists are forested organic soils of Hawaii and other regions which occur on lava flows in areas with very high and well distributed rainfall. This soil covers 11% of the State of Hawaii and represents the State's largest single undeveloped soil resource.

Rainfall, soil temperature and texture of underlying rock are three site parameters which govern the agricultural potential of Tropofolists.

Because of the highly porous nature of the underlying lava, which in most instances occurs within 10 cm (4 inches) from the surface, annual rainfall must be high before this soil can be used for crop production. In the Kona district, with summer rainfall maxima and low evapotranspiration, less rain is required to sustain a forest or agricultural crop than the windward side of the island where winter rains and high wind velocities cause severe water deficit during the summer months.

Above 670 meters (2000 feet) elevation, low soil temperatures and excess cloud cover reduce the agricultural potential of this soil. In addition, the soil is suitable for crop production only when the underlying rock is aa, a loose, clinkery, basaltic lava. The soil is less valuable when it occurs on smooth, billowy, pahoehoe type lava. Forty-three percent of the Tropofolists are underlain by aa lava.

In the land clearing operation most of the organic matter is buried. The remaining organic matter is washed in the subsoil by rains leaving an organic matter free rock pavement. Evaporative water loss from organic matter is reduced in these "inverted" Tropofolists.

Based on current soil survey data, there are about 55,000 acres of Typic Tropofolists which are suitable for crop production. An additional 20,000 acres can be used for agriculture if water resource and a suitable irrigation system can be developed. Lithic Tropofolists or forested organic soils on pahoehoe lava which occurs in the high rainfall belt may have potential for agricultural use. This potential however remains untested.

The greatest need is a detailed soil survey of the high potential areas, particularly to delineate more precisely the boundaries between the Typic (aa) and Lithic (pahoehoe) Tropofolists.

APPENDIX

This Appendix consists of Soil Legends (Tables 12, 13), an Index Map (Figure 20) and Soil Maps (Figures 21-57).

For practical reasons the Soil Maps have been drawn to a scale of 1:96000. For easy identification Tropofolists are indicated by shading. Soil Series names corresponding to map symbols are provided in the Soil Legends.

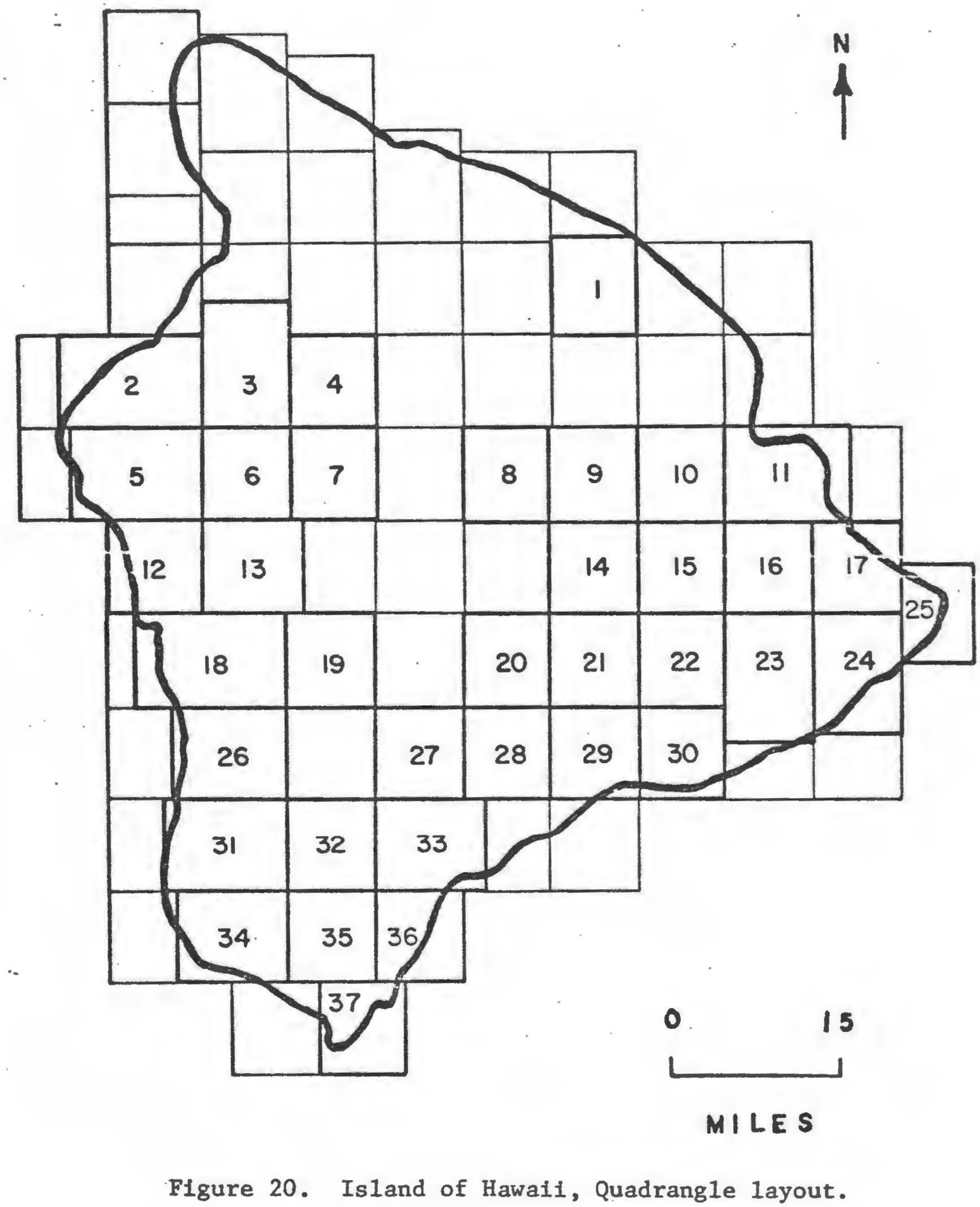

Figure 20. Island of Hawaii, Quadrangle layout.

Tropofolist Quadrangle Layout - Island of Hawaii

1. Keanakolu and part of Kukaiau
2. Kiholo and part of Makalawena
3. Puu Anahulu and part of Puu Hinai
4. Keamuku
5. Kailua and part of Keahole Point
6. Hualalai
7. Naahueleelua
8. Puu Oo
9. Upper Piihonua
10. Piihonua
11. Hilo and part of Keeau Ranch
12. Kealakekua
13. Puu Lehua and part of Puu o Uo
14. Kulani
15. Puu Makaala
16. Mountain View
17. Pahoa North
18. Kaunene and part of Honaunau
19. Sulphur Cone
20. Kipuka Pakekake
21. Kilauea Crater
22. Volcano
23. Kalalua
24. Pahoa South
25. Kapoho
26. Puu Pohakuloa and part of Kauluoa Point
27. Keaiwa Reservoir
28. Wood valley
29. Kau Desert
30. Makaopuhi Crater
31. Papa and part of Milolii
32. Puu o Keokeo
33. Punaluu and part of Pahala
34. Pohue Bay and part of Manuka Bay
35. Kahuku Ranch
36. Naalehu
37. La Lae

Table 12. Soil Legend for Tropofolists

Symbol[a]	Soil Name
rKAD	Kahaluu extremely rocky muck, 6 to 20% slopes
rKED	Kaimu extremely stony peat, 6 to 20% slopes
rKFD	Keaukaha extremely rocky muck, 6 to 20% slopes
rKGD	Keei extremely rocky muck, 6 to 20% slopes
rKHD	Kekake extremely rocky muck, 6 to 20% slopes
rKXD	Kiloa extremely stony muck, 6 to 20% slopes
rKYD	Kona extremely stony muck, 6 to 20% slopes
rLLD	Lalaau extremely stony muck, 6 to 20% slopes
rMAD	Malama extremely stony muck, 6 to 20% slopes
rMWD	Mawae extremely stony muck, 6 to 20% slopes
rOPE	Opihikao extremely rocky muck, 3 to 25% slopes
rPXE	Puna extremely stony muck, 3 to 25% slopes
rPYD	Punaluu extremely rocky peat, 6 to 20% slopes

[a]The first capital letter is the initial one of the soil name. The next letter is a capital if the mapping unit is one of the low intensity or reconnaissance surveys; it is a small letter if the mapping unit is one of the high intensity survey. The last letter, a capital A, B, C, D, E, or F, indicates the slope. Most symbols without a slope letter are those of soils and land types that have a considerable range in slope. A final number, 2 or 3, in the symbol indicates that the soil is eroded or severely eroded. The small letter "r" precedes the symbols for soils of the reconnaissance survey.

Table 13. Soil Legends for Soils Other Than Tropofolists

Symbol	Soil Name
	High Intensity
AaC	Ainakea silty clay loam, 3 to 12% slopes
AaD	Ainakea silty clay loam, 12 to 20% slopes
AaE	Ainakea silty clay loam, 20 to 35% slopes
AkC	Akaka silty clay loam, 0 to 10% slopes
AkD	Akaka silty clay loam, 10 to 20% slopes
AlC	Alapai silty clay loam, 0 to 10% slopes
AlD	Alapai silty clay loam, 10 to 20% slopes
AlE	Alapai silty clay loam, 20 to 35% slopes
ApD	Alapai extremely stony silty clay loam, 10 to 20% slopes
HaA	Hawi silty clay, 0 to 3% slopes
LAD	Laumaia silt loam, 6 to 20% slopes
LUC	Laumaia extremely stony silt loam, 6 to 12% slopes
MHC	Mahukona silty clay loam, 3 to 12% slopes
MKC	Mahukona very stony silty clay loam, 6 to 12% slopes
MLD	Maile silt loam, 6 to 20% slopes
MMD	Manahaa silt loam, 6 to 20% slopes
MND	Manahaa extremely stony silt loam, 6 to 20% slopes
MSD	Mawae extremely stony muck, 6 to 20% slopes
MT	Mixed alluvial land
OHC	Ohia silty clay loam, 0 to 10% slopes
OSD	Ohia extremely stony silty clay loam, 0 to 20% slopes
PKB	Pakini very fine sandy loam, 2 to 6% slopes

Table 13. (Continued) Soil Legends for Soils Other Than Tropofolists

Symbol	Soil Name
PLC	Palapalai silty loam, 6 to 12% slopes
PMC	Palapalai silty clay loam, 6 to 12% slopes
PND	Piihonua silty clay loam, 6 to 20% slopes
POD	Piihonua extremely stony silty clay loam, 6 to 20% slopes
PPC	Puaulu silt loam, 0 to 10% slopes
PRD	Punohu silt loam, 12 to 20% slopes
PSC	Puukala extremely stony silt loam, 6 to 12% slopes
PTC	Puukala very rocky silt loam, 6 to 12% slopes
PUC	Puu Oo silt loam, 6 to 12% slopes
PVD	Puu Pa extremely stony very fine sandy loam, 6 to 20% slopes
PVF3	Puu Pa extremely stony very fine sandy loam, 70 to 10% slopes, severely eroded
PWD	Puu Pa silt loam, 12 to 20% slopes
HaC	Hawi silty clay, 3 to 12% slopes
HeC	Hawi extremely stony silty clay, 6 to 12% slopes
HlC	Hilea silty clay loam, 6 to 12% slopes
HoC	Hilo silty clay loam, 0 to 10% slopes
HoD	Hilo silty clay loam, 10 to 20% slopes
HoE	Hilo silty clay loam, 20 to 35% slopes
HsC	Honokaa silty clay loam, low elevation, 0 to 10% slopes
HsD	Honokaa silty clay loam, low elevation, 10 to 20% slopes
HsE	Honokaa silty clay loam, low elevation, 20 to 35% slopes
KaC	Kaiwiki silty clay loam, 0 to 10% slopes

Table 13. (Continued) Soil Legends for Soils Other Than Tropofolists

Symbol	Soil Name
KaD	Kaiwiki silty clay loam, 10 to 20% slopes
KaE	Kaiwiki silty clay loam, 20 to 35% slopes
KfA	Kikoni very fine sandy loam, 0 to 3% slopes
KhA	Kohala silty clay, 0 to 3% slopes
KhC	Kohala silty clay, 3 to 12% slopes
KhD	Kohala silty clay, 12 to 20% slopes
KhE	Kohala silty clay, 20 to 35% slopes
KuC	Kukaiau silty clay loam, 6 to 12% slopes
KuD	Kukaiau silty clay loam, 12 to 20% slopes
KuE	Kukaiau silty clay loam, 20 to 35% slopes
KwD	Kukaiau silty clay loam, moderately shallow, 12 to 20% slopes
MaA	Maile silt loam, 0 to 3% slopes
MoC	Moaula silty clay loam, 0 to 10% slopes
MoD	Moaula silty clay loam, 10 to 20% slopes
MoE	Moaula silty clay loam, 20 to 35% slopes
NaC	Naalehu silty clay loam, 0 to 10% slopes
NaD	Naalehu silty clay loam, 10 to 20% slopes
NaE	Naalehu silty clay loam, 20 to 35% slopes
NhD	Naalehu very rocky silty clay loam, 6 to 20% slopes
NlC	Niulii silty clay loam, 6 to 12% slopes
NlD	Niulii silty clay loam, 12 to 20% slopes
NlE	Niulii silty clay loam, 20 to 35% slopes

Table 13. (Continued) Soil Legends for Soils Other Than Tropofolists

Symbol	Soil Name
OaC	Olaa silty clay loam, 0 to 10% slopes
OlD	Olaa extremely stony silty clay loam, 0 to 20% slopes
OoC	Ookala silty clay loam, 6 to 12% slopes
OoD	Ookala silty clay loam, 12 to 20% slopes
OoE	Ookala silty clay loam, 20 to 35% slopes
PaC	Paauhau silty clay loam, 6 to 12% slopes
PaD	Paauhau silty clay loam, 12 to 20% slopes
PaE	Paauhau silty clay loam, 20 to 35% slopes
PeC	Panaewa very rocky silty clay loam, 0 to 10% slopes
Tr	Tropaquepts
	Low Intensity
AFD	Apakuie very fine sandy loam, 12 to 20% slopes
ASD	Apakuie very stony very fine sandy loam, 12 to 20% slopes
BH	Beaches
FL	Fill land
HCD	Hanipoe very stony loam, 12 to 20% slopes
HDD	Hanipoe silt loam, 12 to 20% slopes
HFD	Hanipoe very rocky silt loam, 6 to 20% slopes
HHC	Heake very rocky sandy loam, 6 to 12% slopes
HKC	Heake extremely rocky sandy loam, 0 to 10% slopes
HND	Honaunau silt loam, 6 to 20% slopes
HRD	Honaunau extremely rocky silty clay loam, 6 to 20% slopes

Table 13. (Continued) Soil Legends for Soils Other Than Tropofolists

Symbol	Soil Name
HTD	Honokaa silty clay loam, 10 to 20% slopes
HTE	Honokaa silty clay loam, 20 to 35% slopes
HUD	Honuaulu very stony silty clay loam, 6 to 20% slopes
HVD	Honuaulu extremely stony silty clay loam, 12 to 20% slopes
KBC	Kaalualu extremely stony loamy sand, 2 to 12% slopes
KCD	Kahua silty clay loam, 6 to 20% slopes
KDD	Kainaliu very stony silty clay loam, 12 to 20% slopes
KEC	Kainaliu extremely stony silty clay loam, 12 to 20% slopes
KGC	Kamakoa very fine sandy loam, 0 to 10% slopes
KIC	Kamaoa loam, 6 to 12% slopes
KJC	Kamaoa loam, moderately shallow, 6 to 12% slopes
KKC	Kamaoa extremely stony loam, 6 to 12% slopes
KLC	Kapapala loam, 0 to 10% slopes
KLD	Kapapala loam, 10 to 20% slopes
KMD	Kapapala very rocky loam, 6 to 20% slopes
KNC	Kawaihae extremely stony very fine sandy loam, 6 to 12% slopes
KOC	Kawaihae very rocky very fine sandy loam, 6 to 12% slopes
KPD	Kealakekua silty clay loam, 12 to 20% slopes
KRD	Kealakekua very stony silty clay loam, 6 to 20% slopes
KSD	Kealakekua extremely stony silty clay loam, 12 to 20% slopes
KTB	Keekee loamy sand, 0 to 6% slopes
KVC	Kehena silty clay loam, 6 to 12% slopes

Table 13. (Continued) Soil Legends for Soils Other Than Tropofolists

Symbol	Soil Name
KXC	Kikoni very fine sandy loam, 3 to 12% slopes
KYC	Kikoni extremely stony very fine sandy loam, 6 to 12% slopes
KZD	Kilohana loamy fine sand, 12 to 20% slopes
RB	Rough broken land
UMD	Umikoa silt loam, 12 to 20% slopes
USD	Umikoa extremely stony silt loam, 12 to 20% slopes
WAC	Waiaha silt loam, 0 to 10% slopes
WAD	Waiaha silt loam, 10 to 20% slopes
WHC	Waiaha extremely stony silt loam, 6 to 12% slopes
WKD	Waiaha very rocky silt loam, 10 to 20% slopes
WLC	Waikaloa very fine sandy loam, 6 to 12% slopes
WMC	Waimea very fine sandy loam, 6 to 12% slopes
WSD	Waimea extremely stony very fine sandy loam, 12 to 20% slopes
	Reconnaissance
rAK	Akaka soils
rAM	Amalu soils
rAR	Amalu-Rough broken land association
rCL	Cinder land
rHID	Huikau loamy sand, 12 to 20% slopes
rHID2	Huikau loamy sand, 12 to 20% slopes, eroded
rHLD	Huikau extremely stony loamy sand, 12 to 20% slopes
rHP	Hydrandept-Tropofolist association
rKUC	Kilauea extremely gravelly sand, 6 to 12% slopes
rLV	Lava flows, aa

Table 13. (Continued) Soil Legends for Soils Other Than Tropofolists

Symbol	Soil Name
rLW	Lava flows, pahoehoe
rMUB	Mana silt loam, 2 to 6% slopes
rPHB	Puhimau silt loam, 2 to 6% slopes
rRO	Rock land
rVS	Very stony land

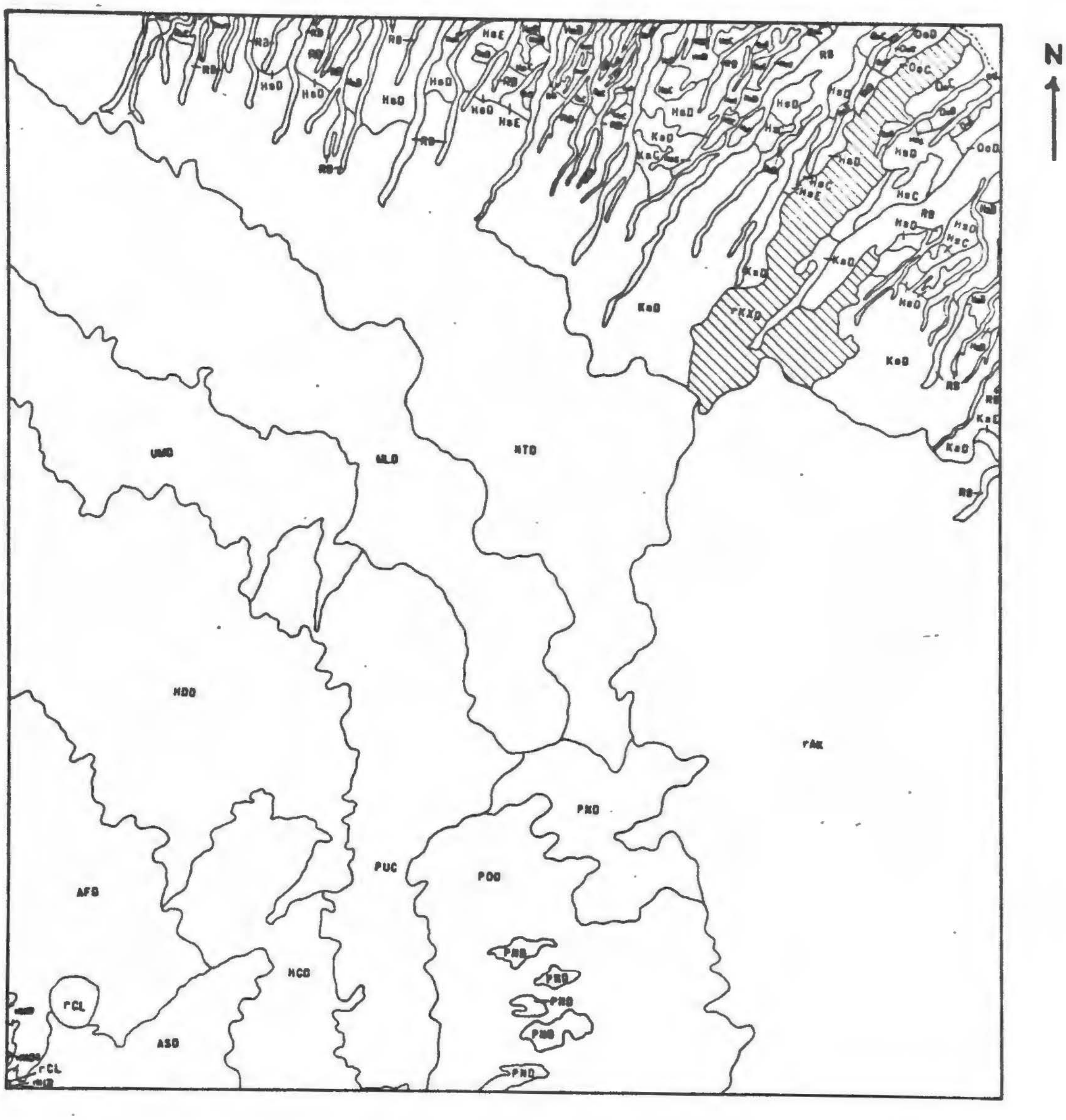

Figure 21. Tropofolists: Quadrangle 1.

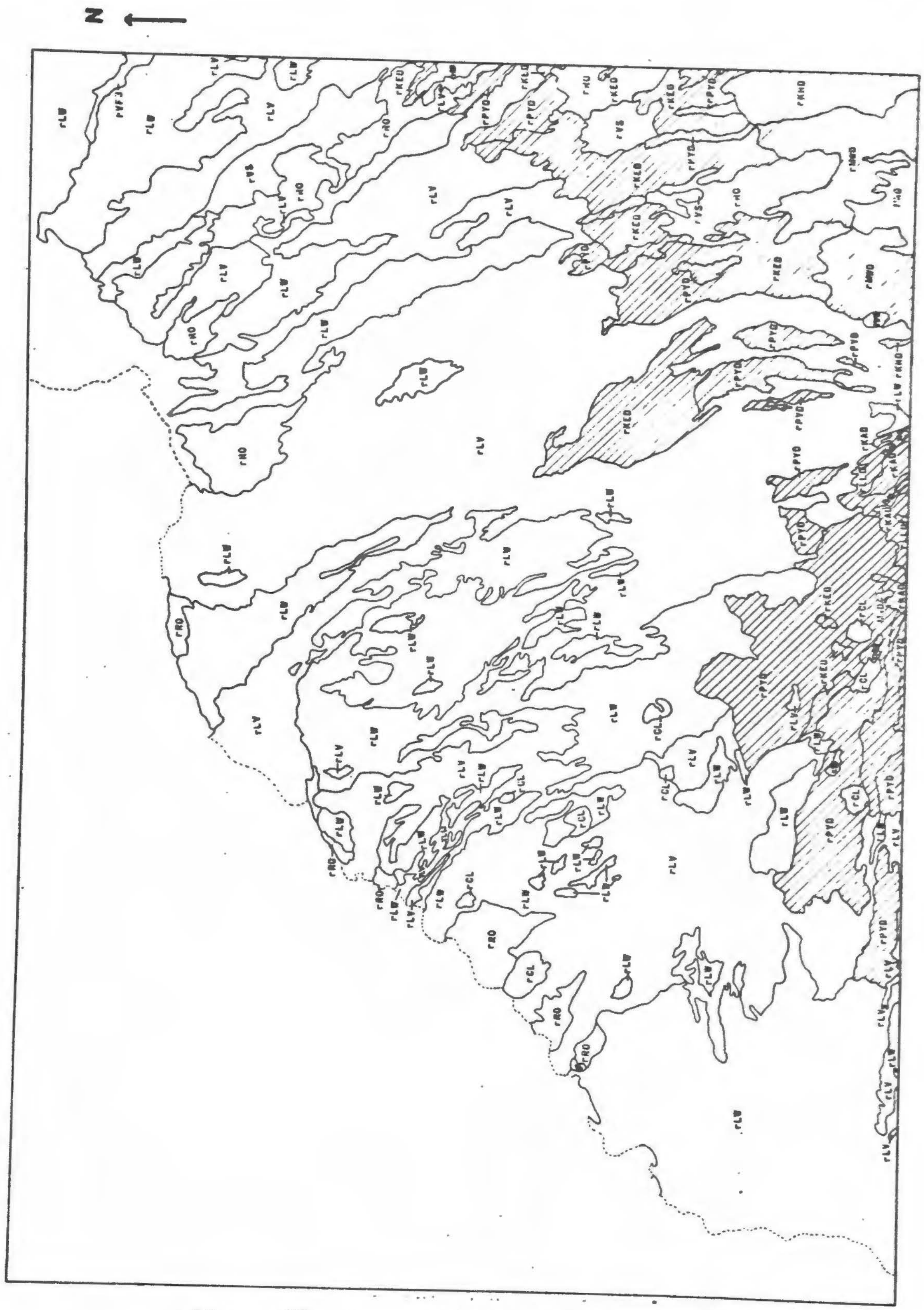

Figure 22. Tropofolists: Quadrangle 2.

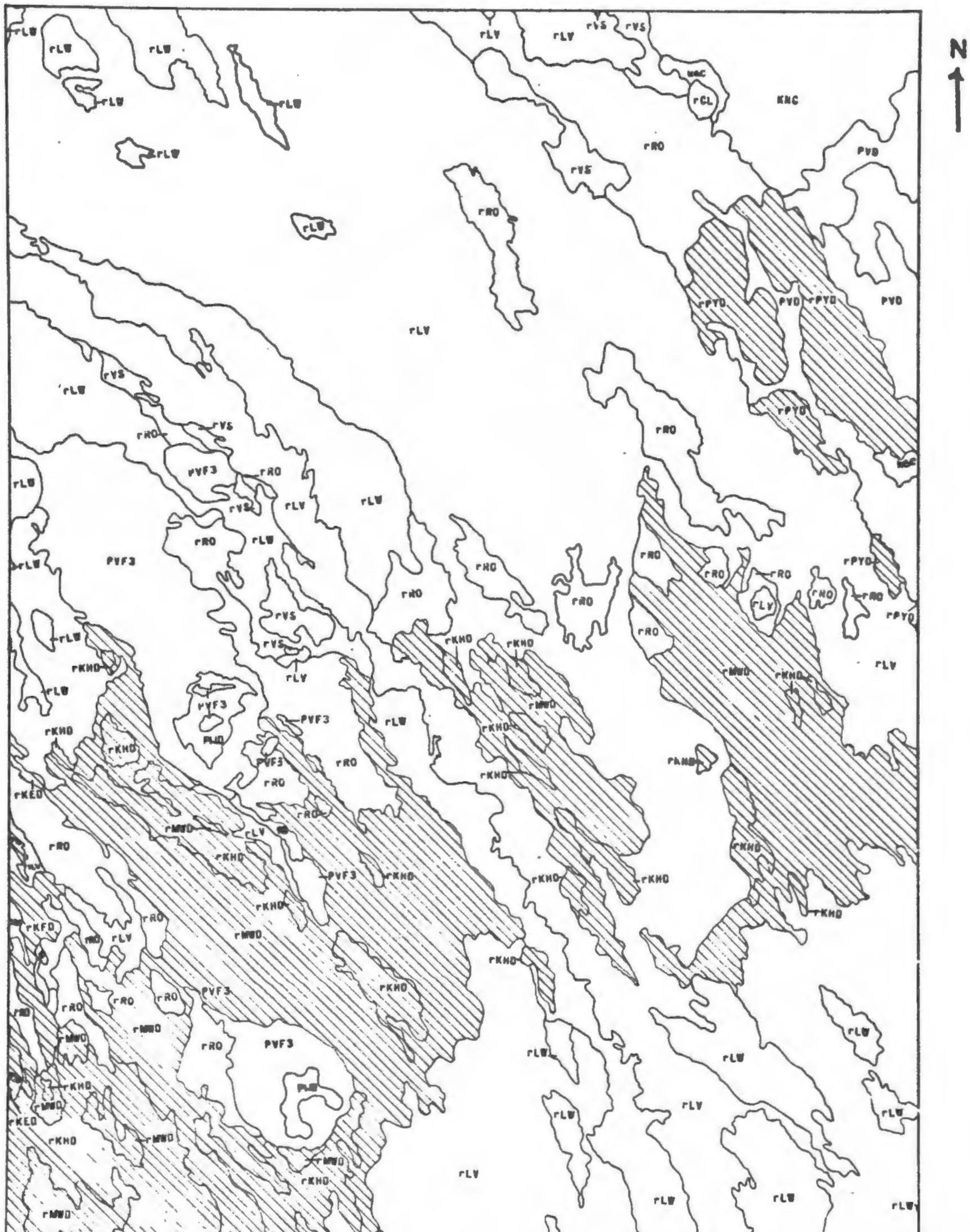

Figure 23. Tropofolists: Quadrangle 3.

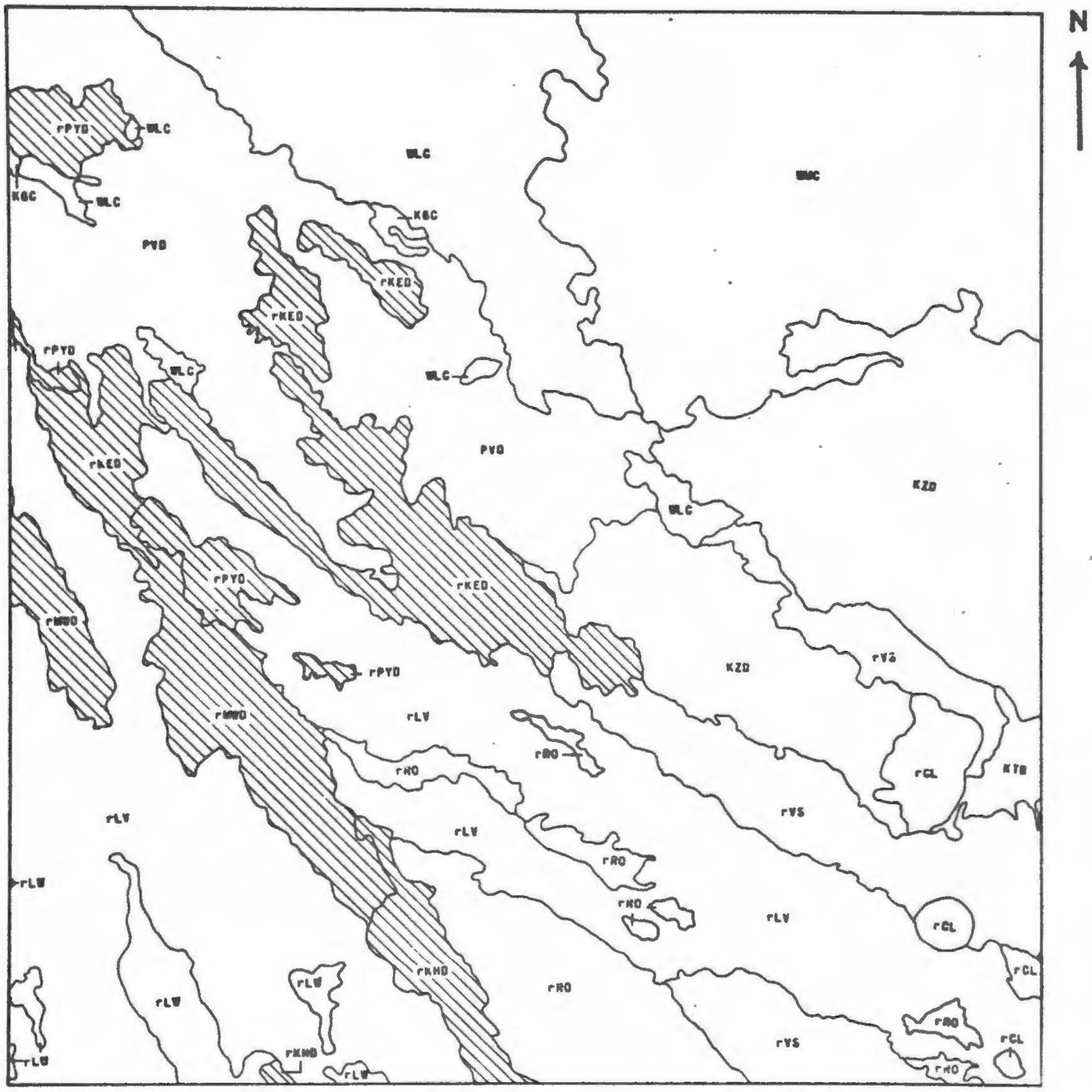

Figure 24. Tropofolists: Quadrangle 4.

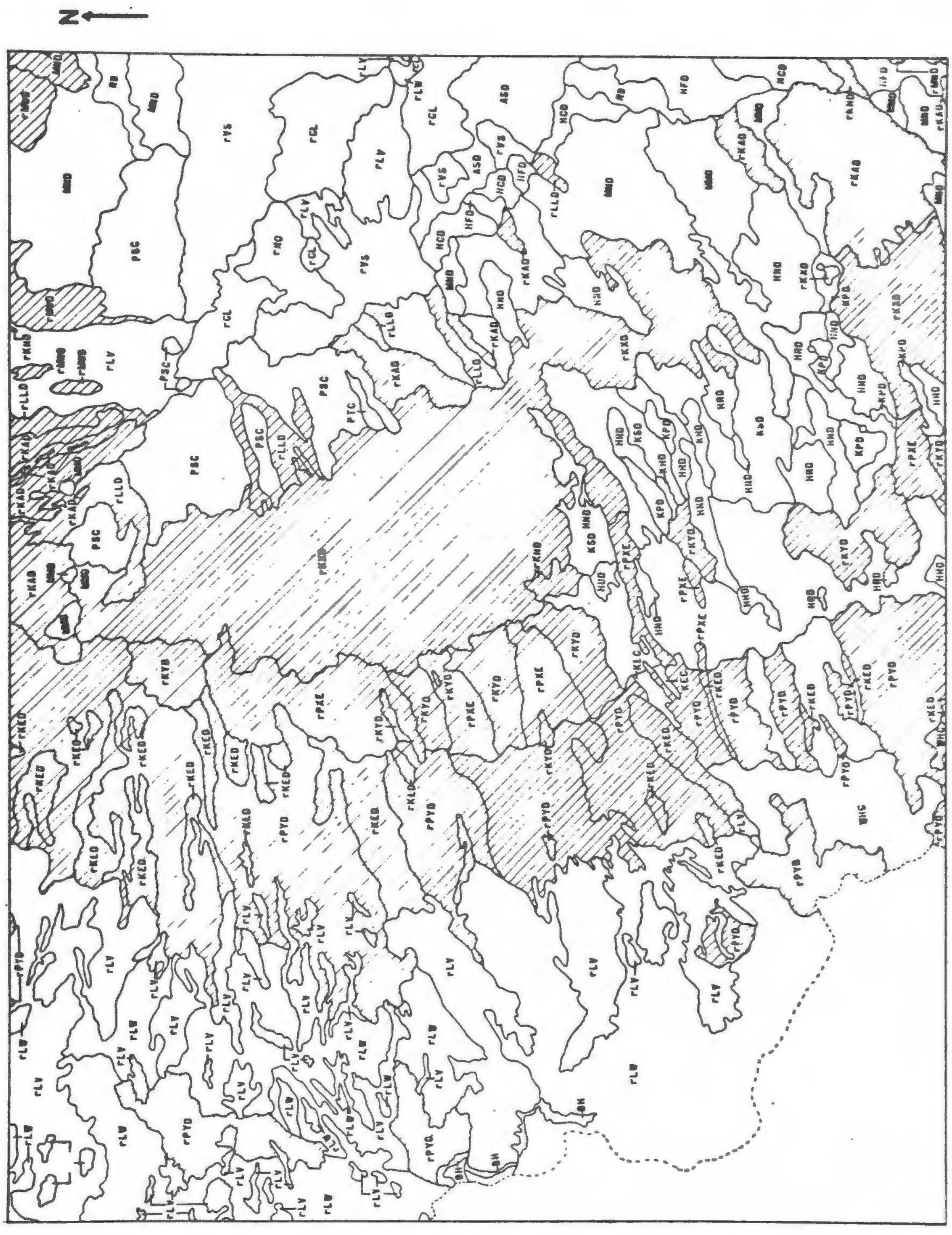

Figure 25. Tropofolists: Quadrangle 5.

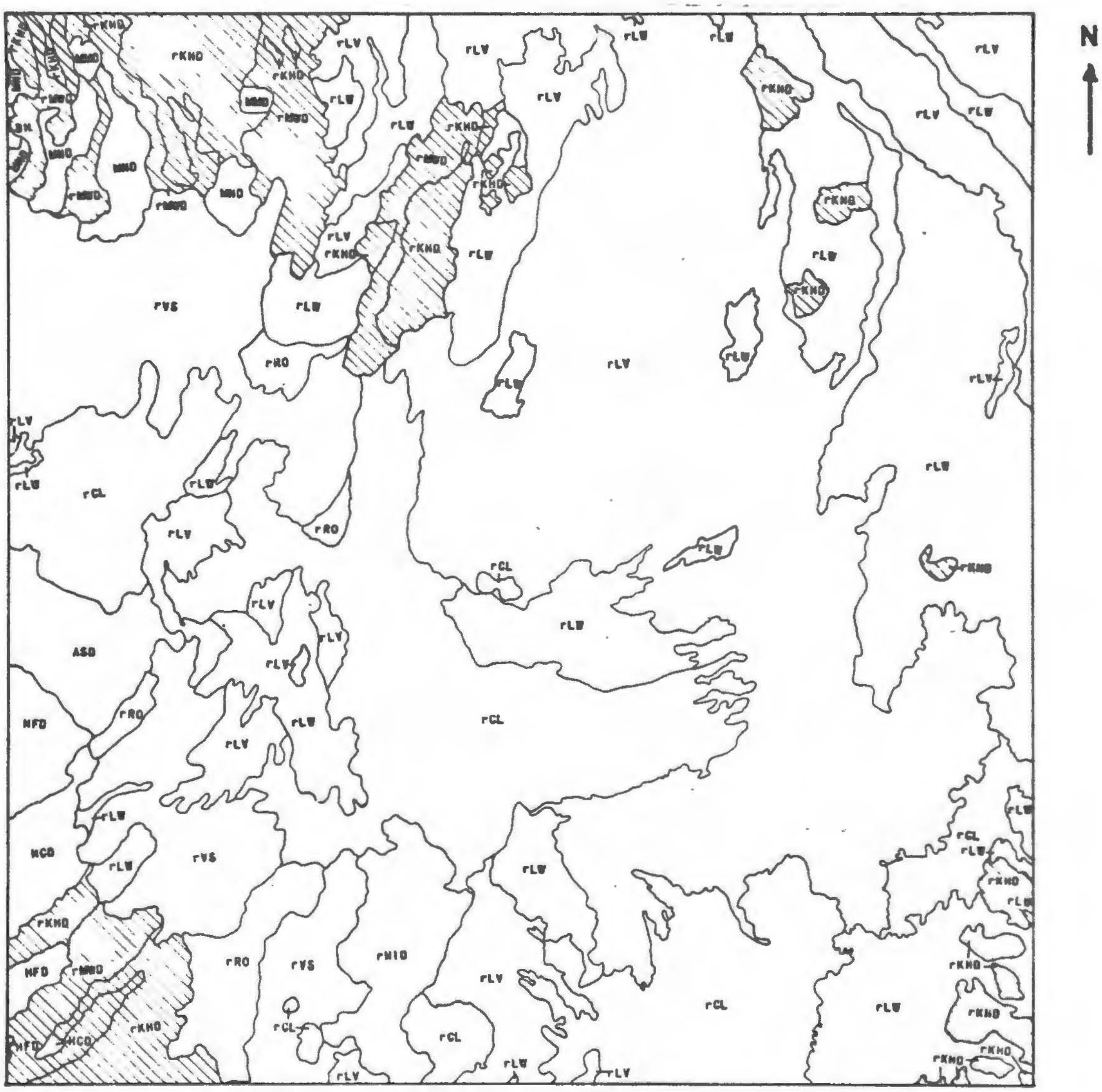

Figure 26. Tropofolists: Quadrangle 6.

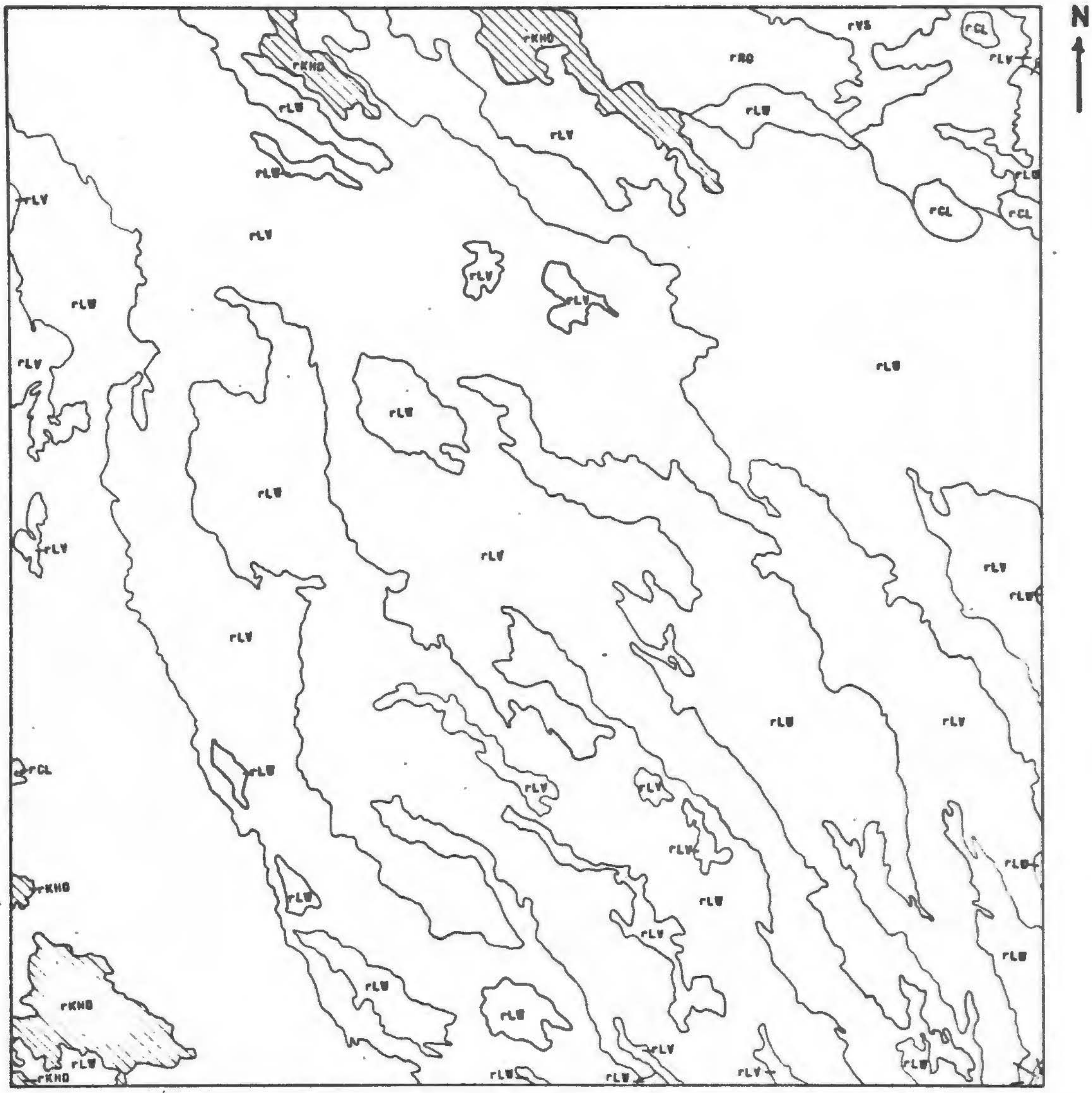

Figure 27. Tropofolists: Quadrangle 7.

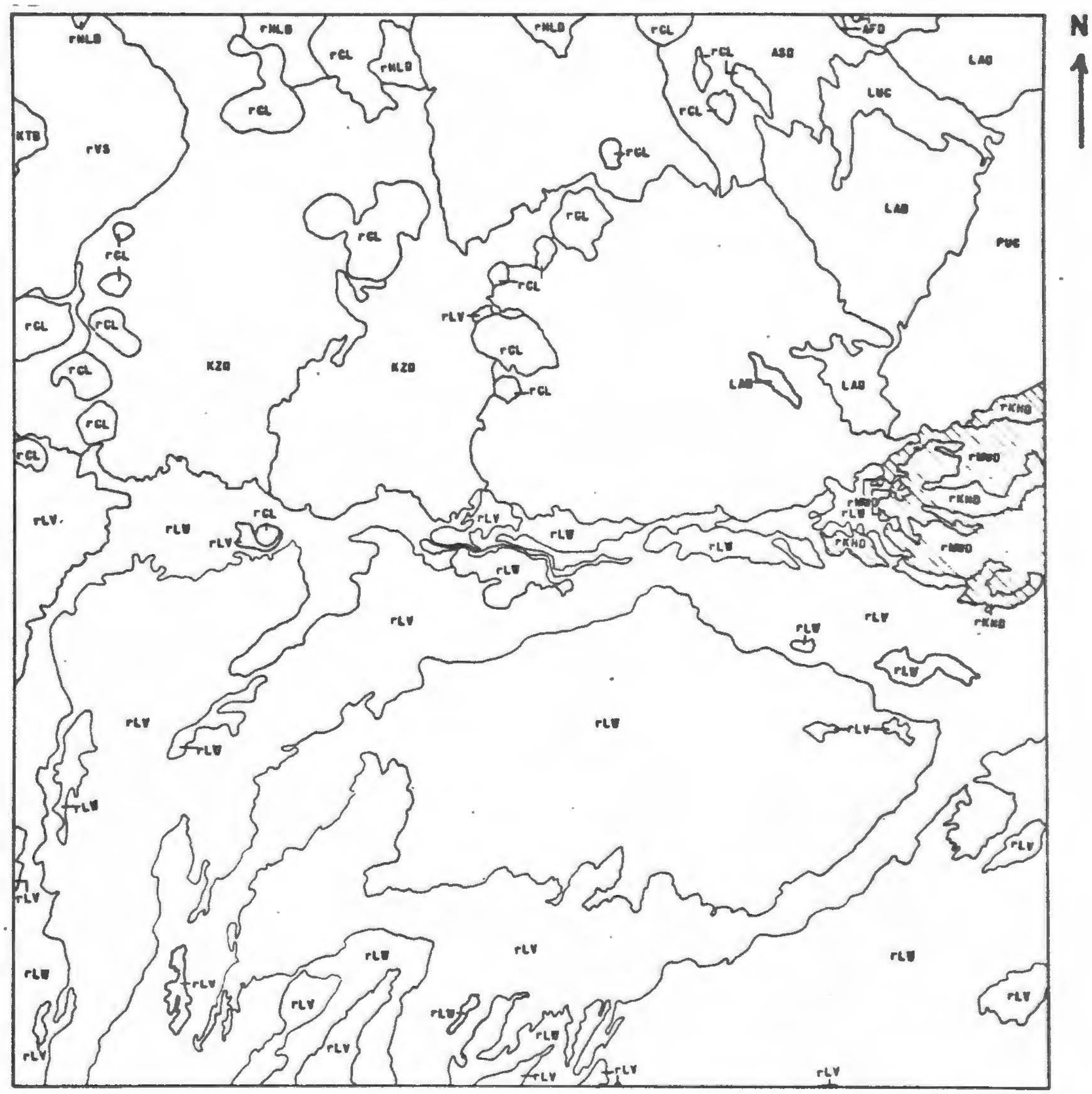

Figure 28. Tropofolists: Quadrangle 8.

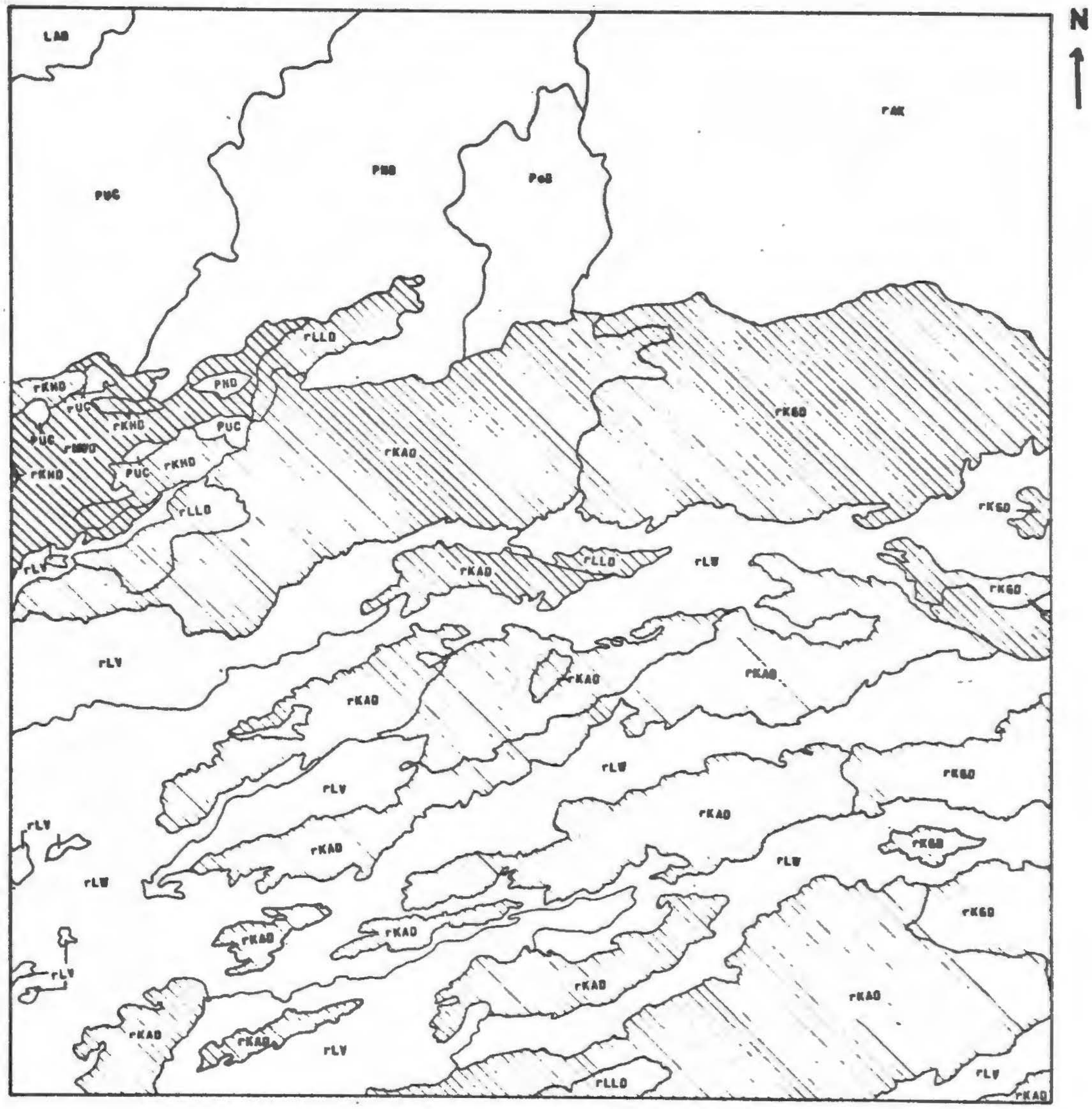

Figure 29. Tropofolists: Quadrangle 9.

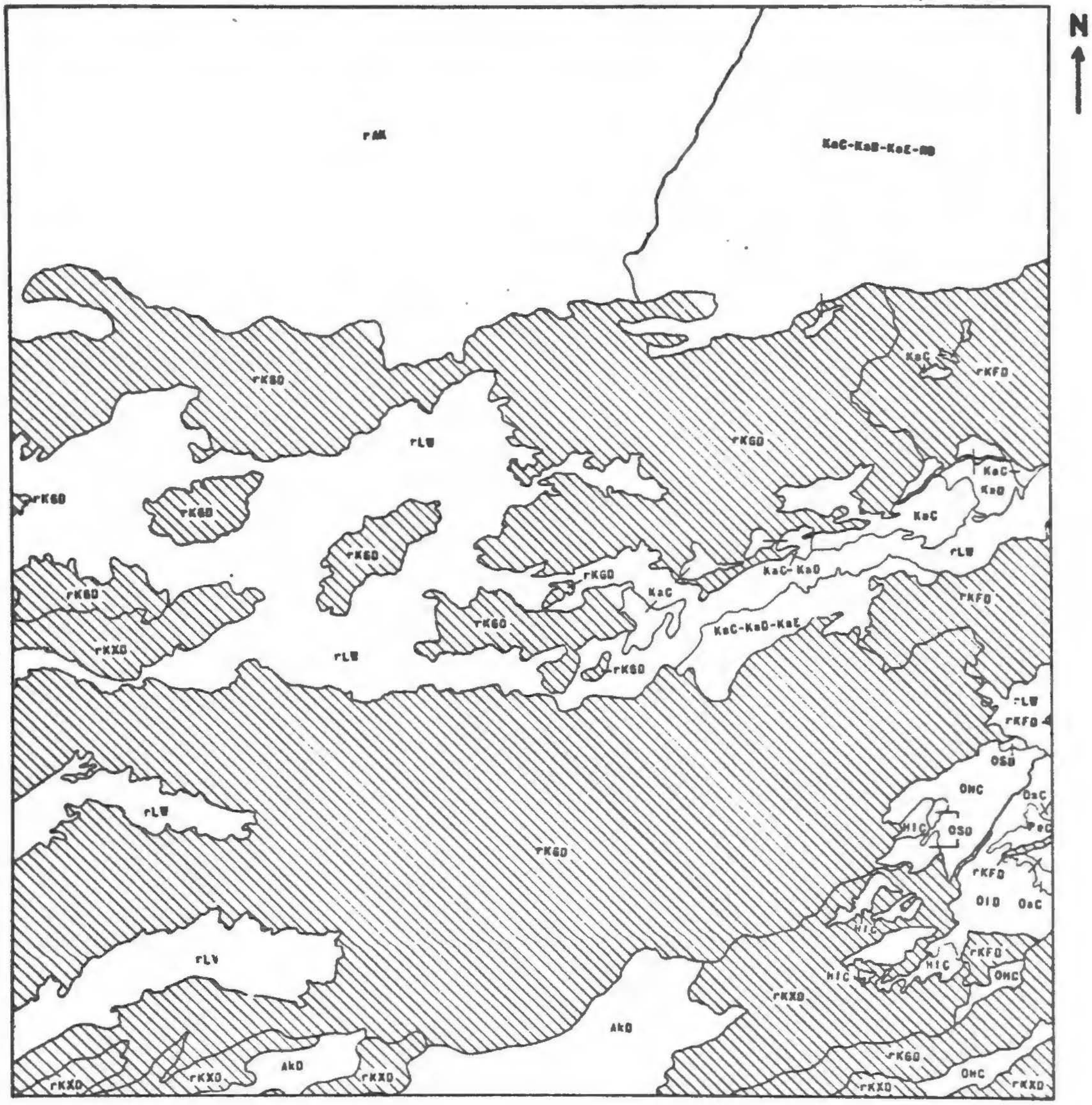

Figure 30. Tropofolists: Quadrangle 10.

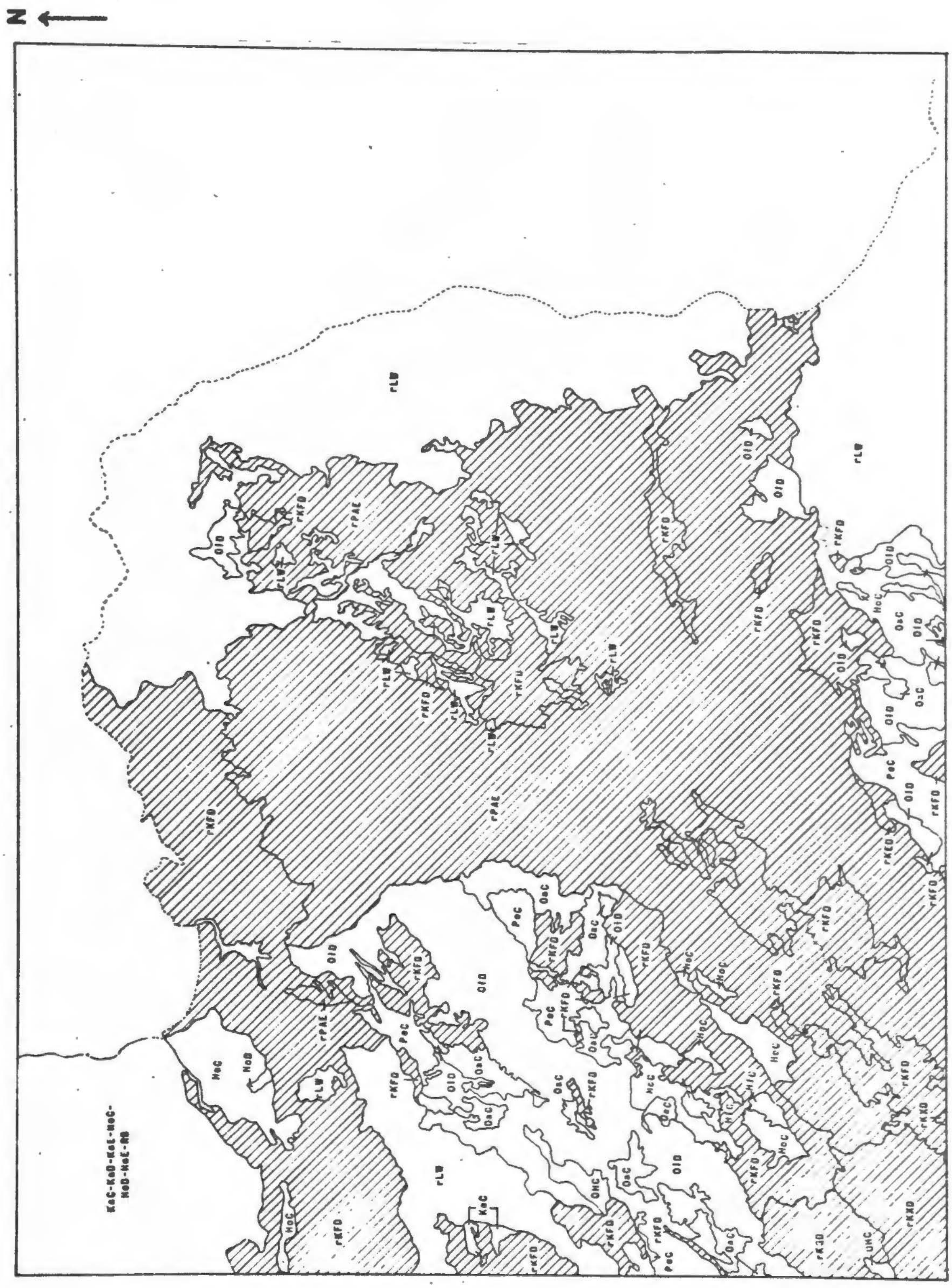

Figure 31. Tropofolists: Quadrangle 11.

Figure 32. Tropofolists: Quadrangle 12.

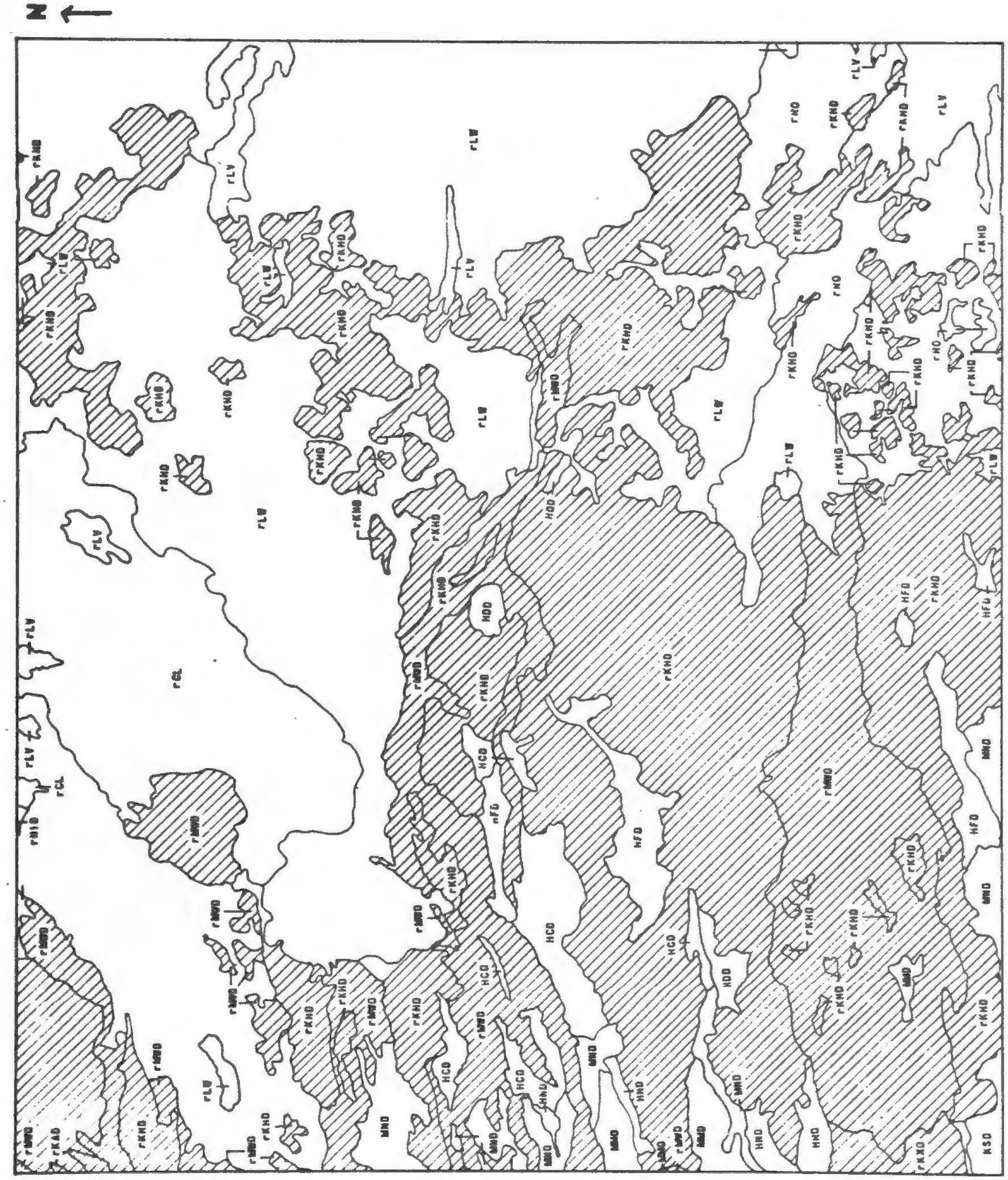

Figure 33. Tropofolists: Quadrangle 13.

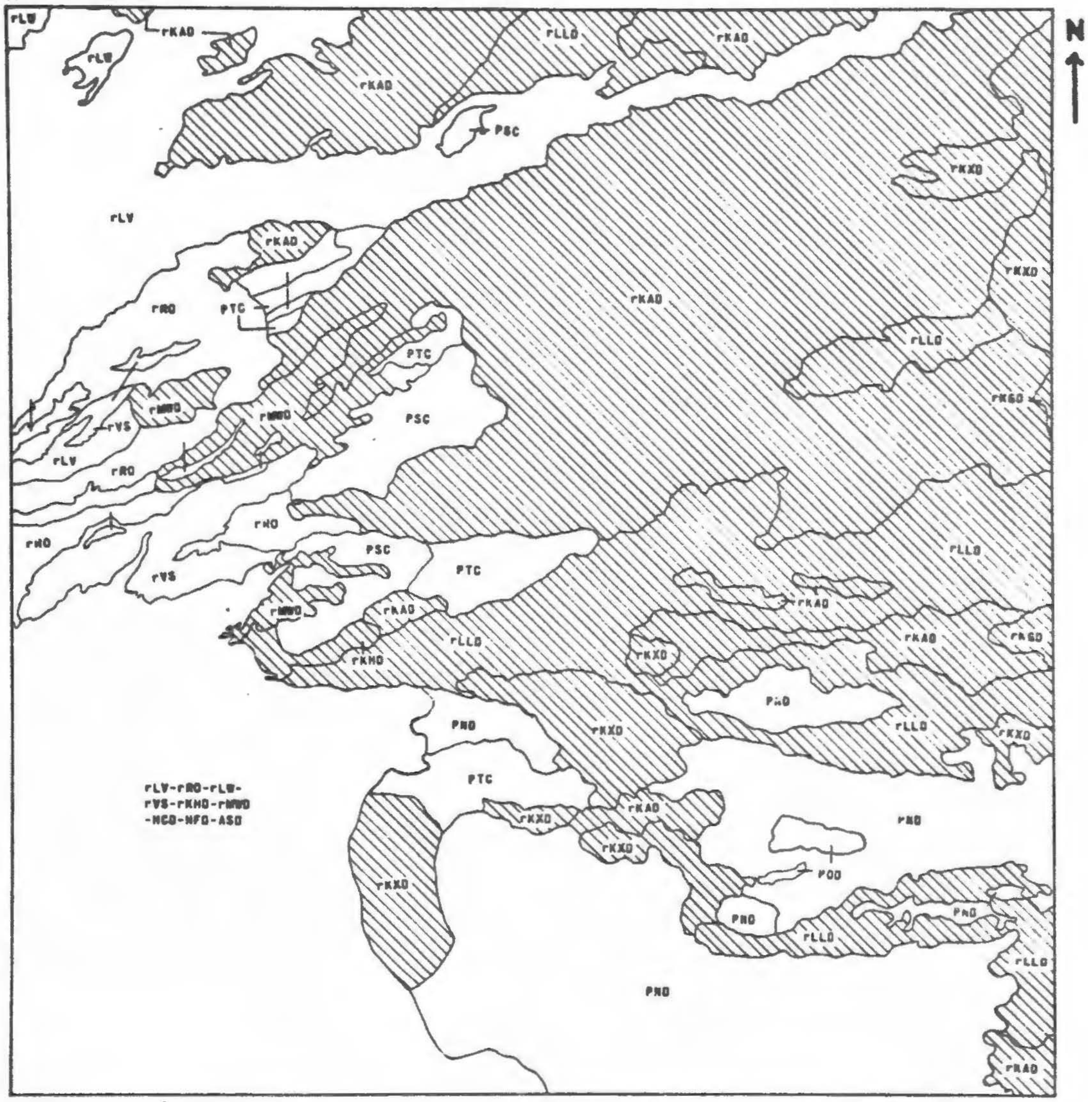

Figure 34. Tropofolists: Quadrangle 14.

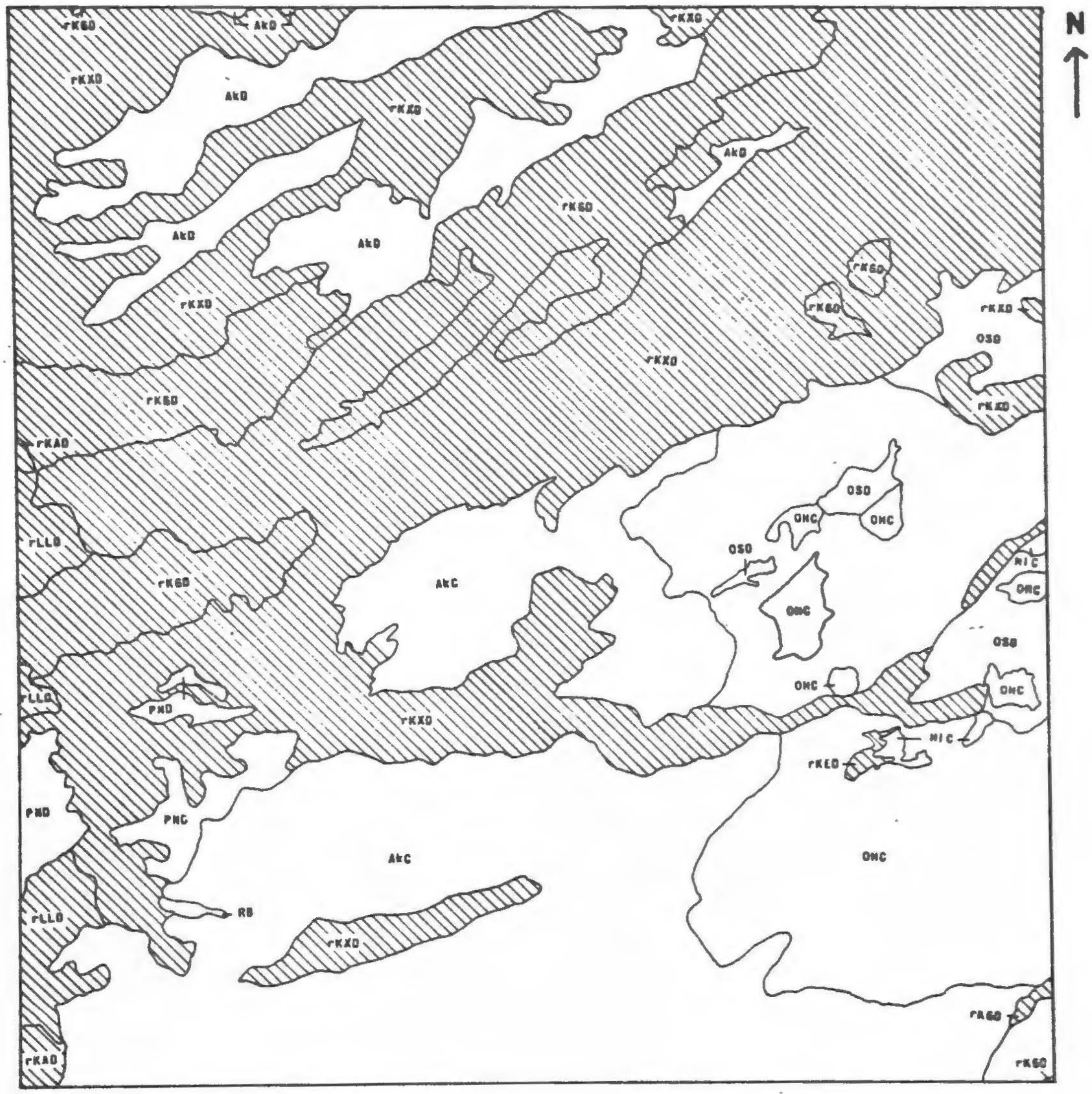

Figure 35. Tropofolists: Quadrangle 15.

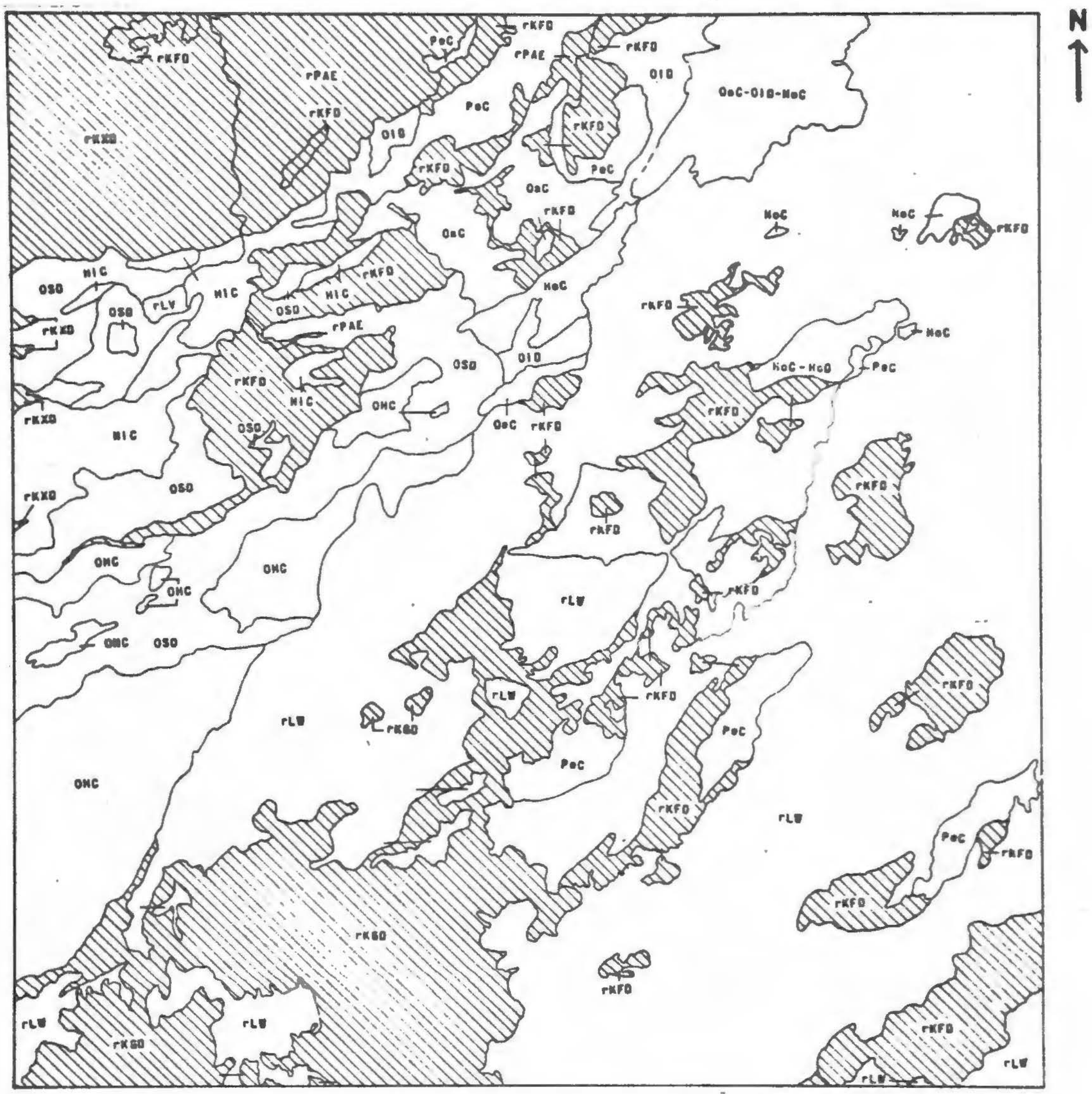

Figure 36. Tropofolists: Quadrangle 16.

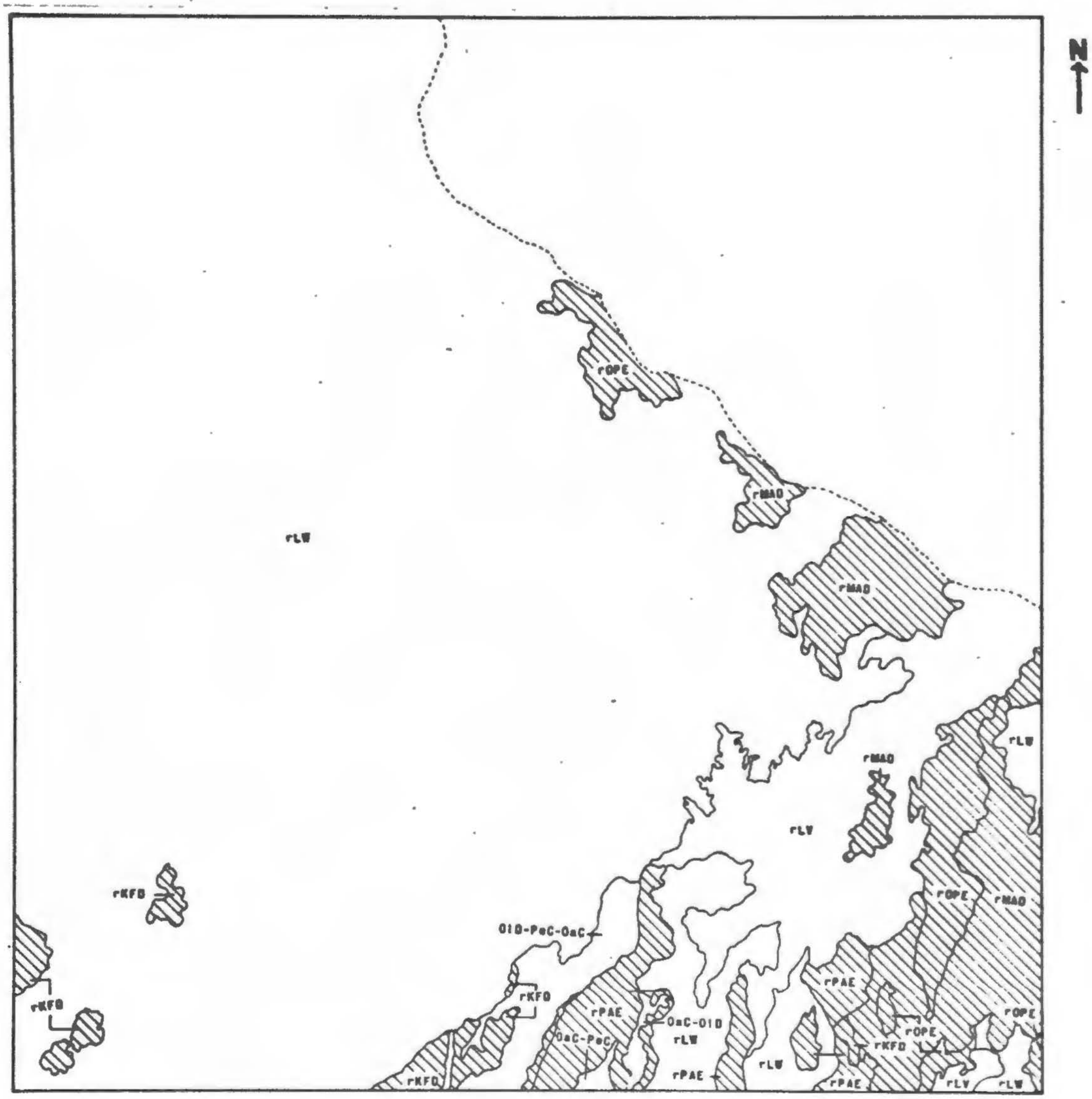

Figure 37. Tropofolists: Quadrangle 17.

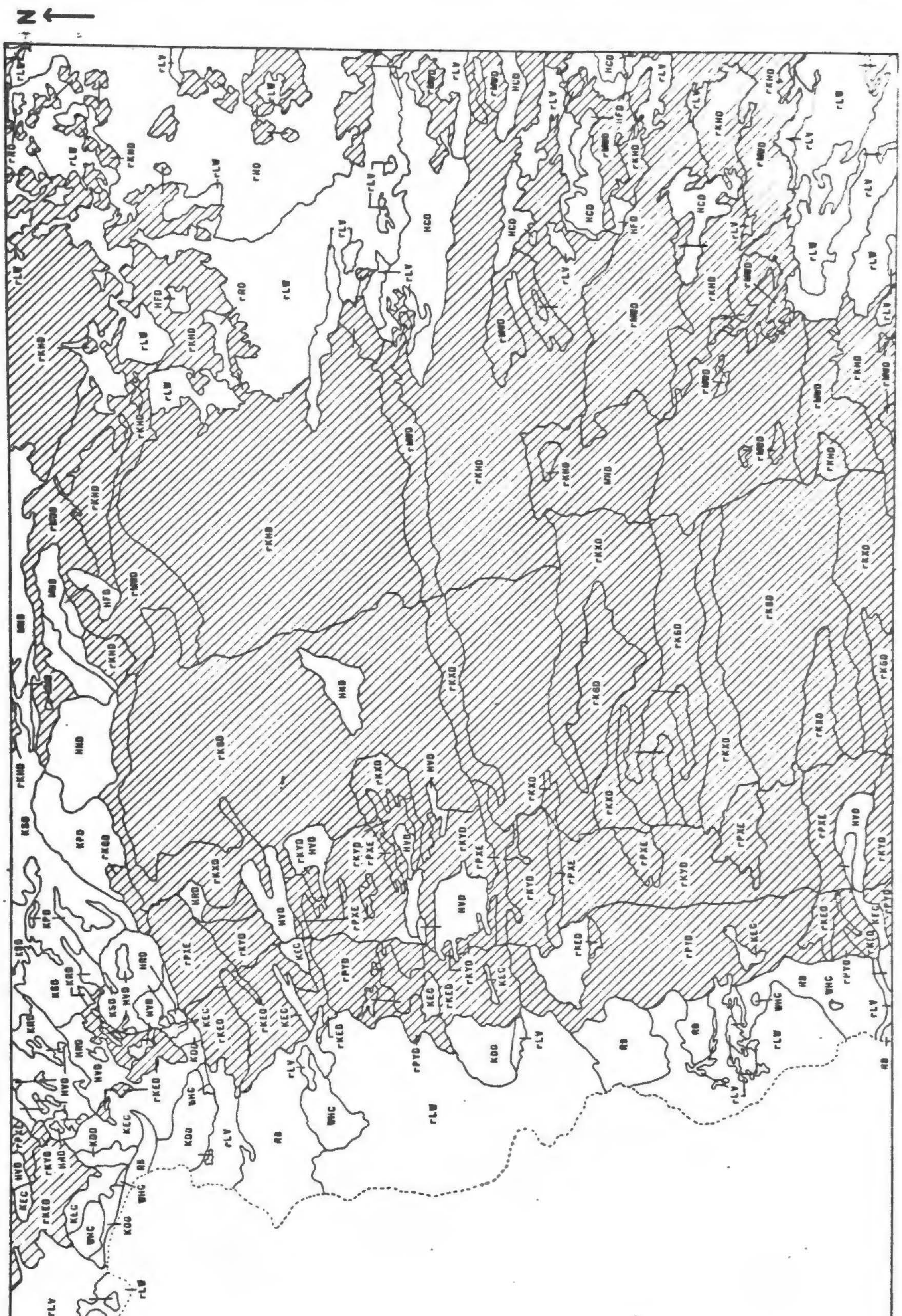

Figure 38. Tropofolists: Quadrangle 18.

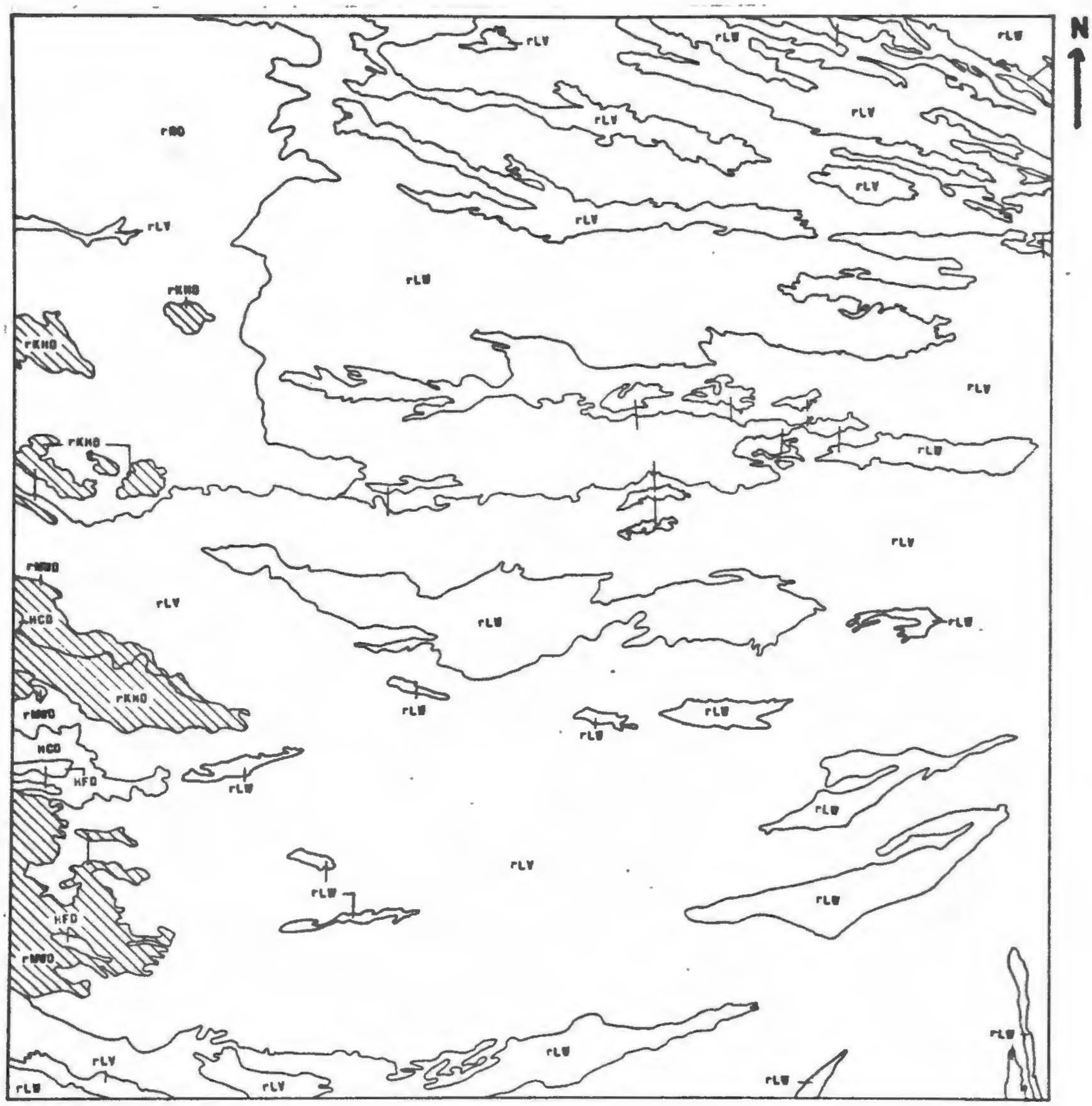

Figure 39. Tropofolists: Quadrangle 19.

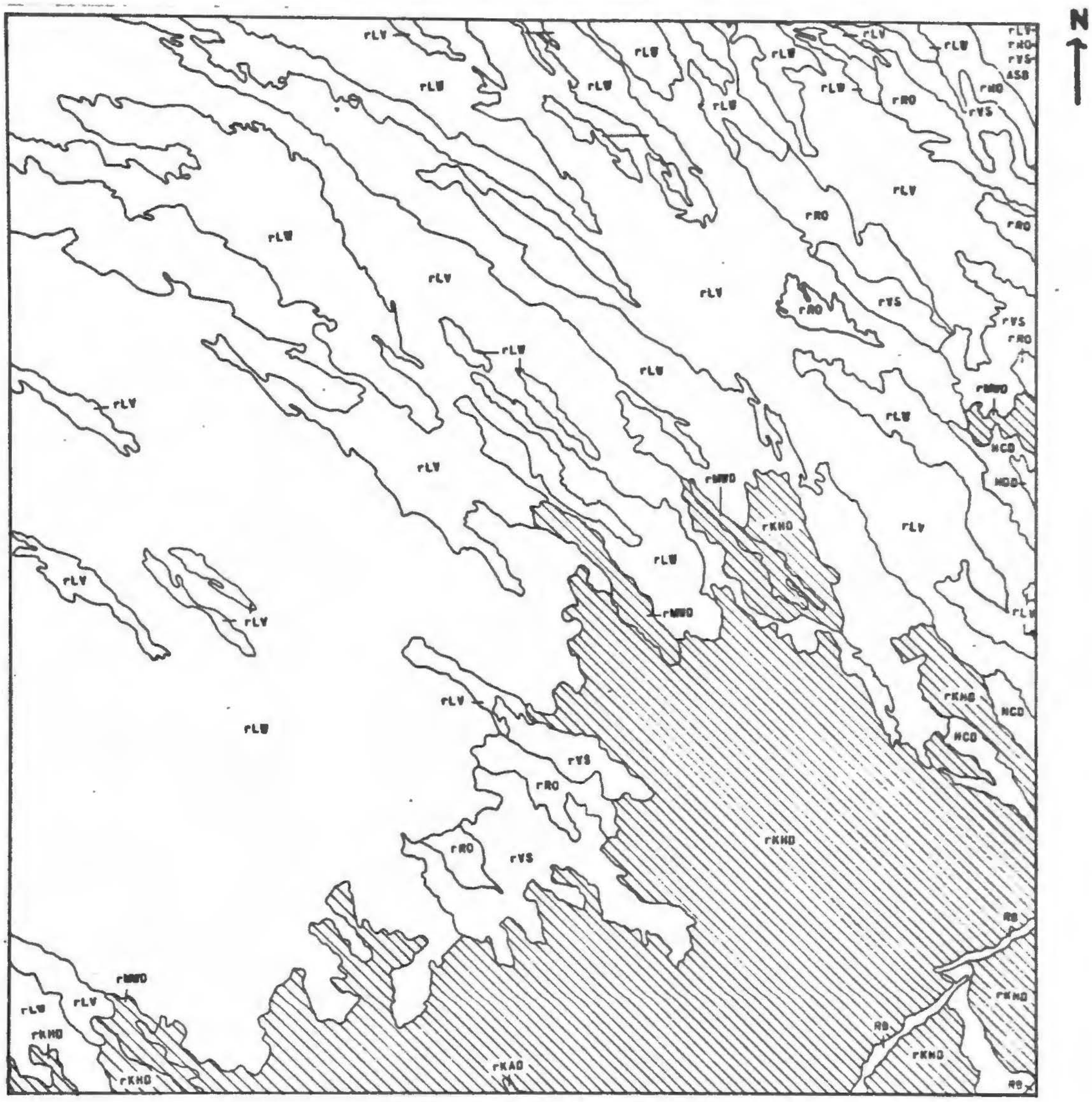

Figure 40. Tropofolists: Quadrangle 20.

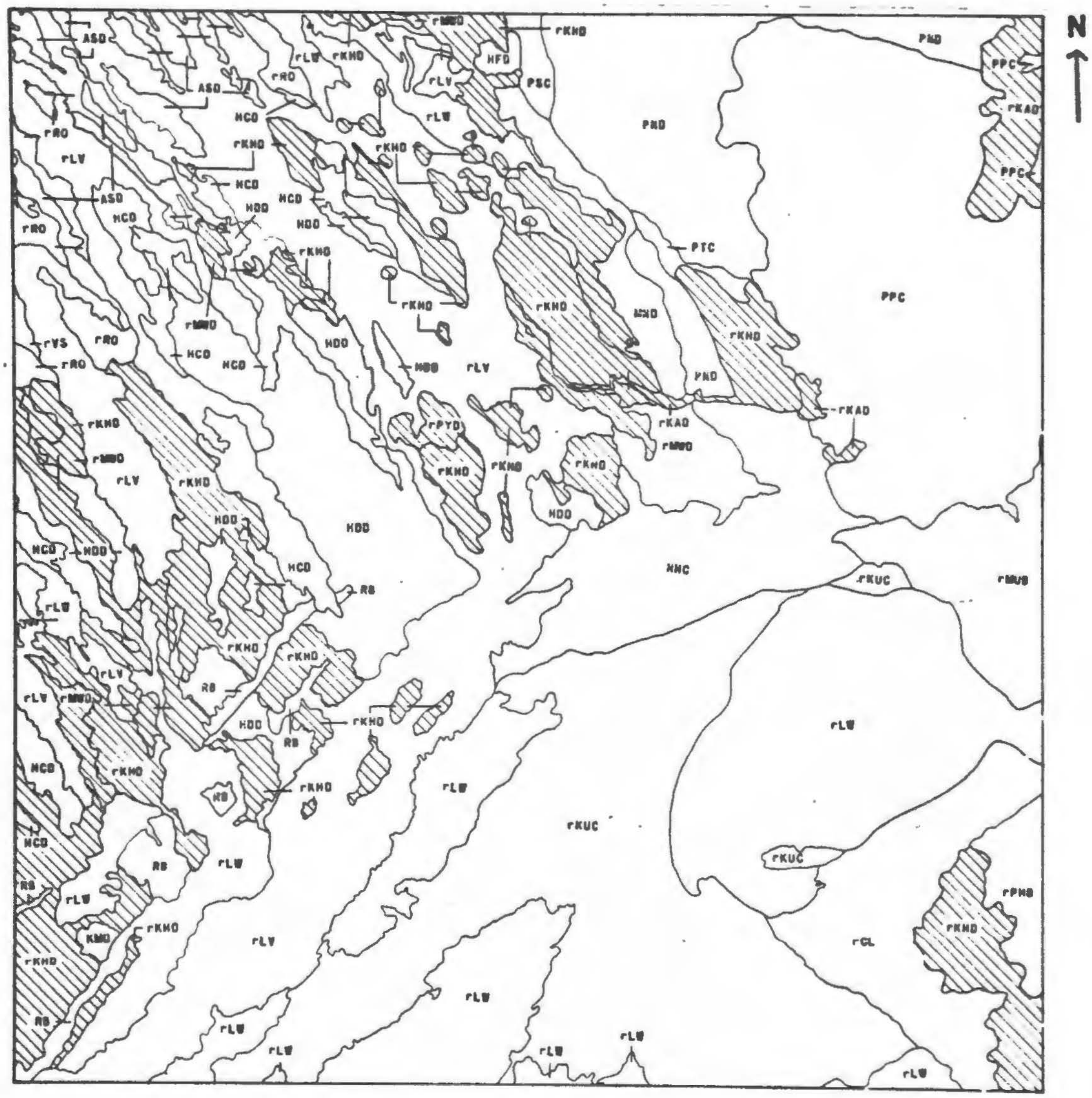

Figure 41. Tropofolists: Quadrangle 21.

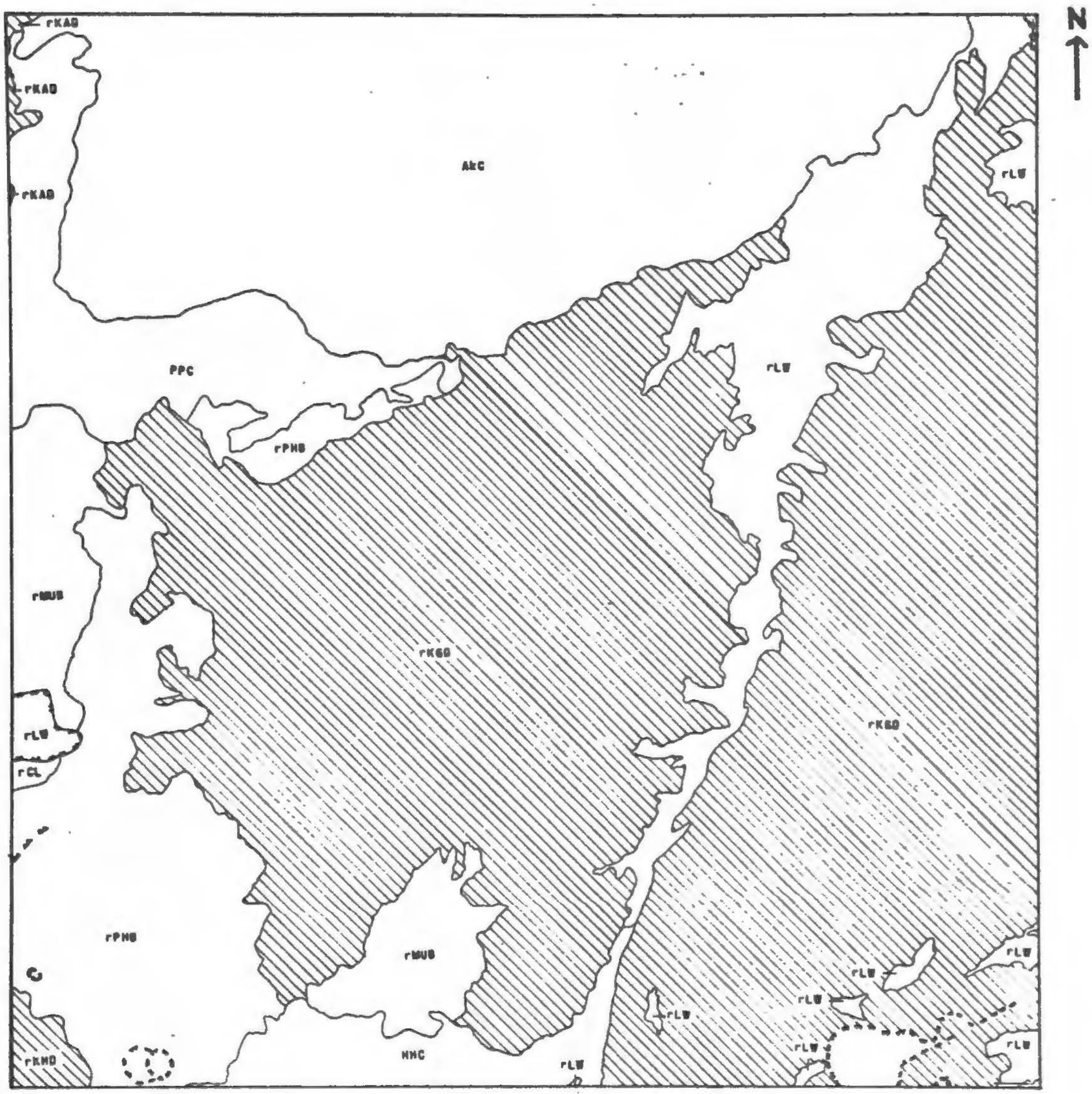

Figure 42. Tropofolists: Quadrangle 22.

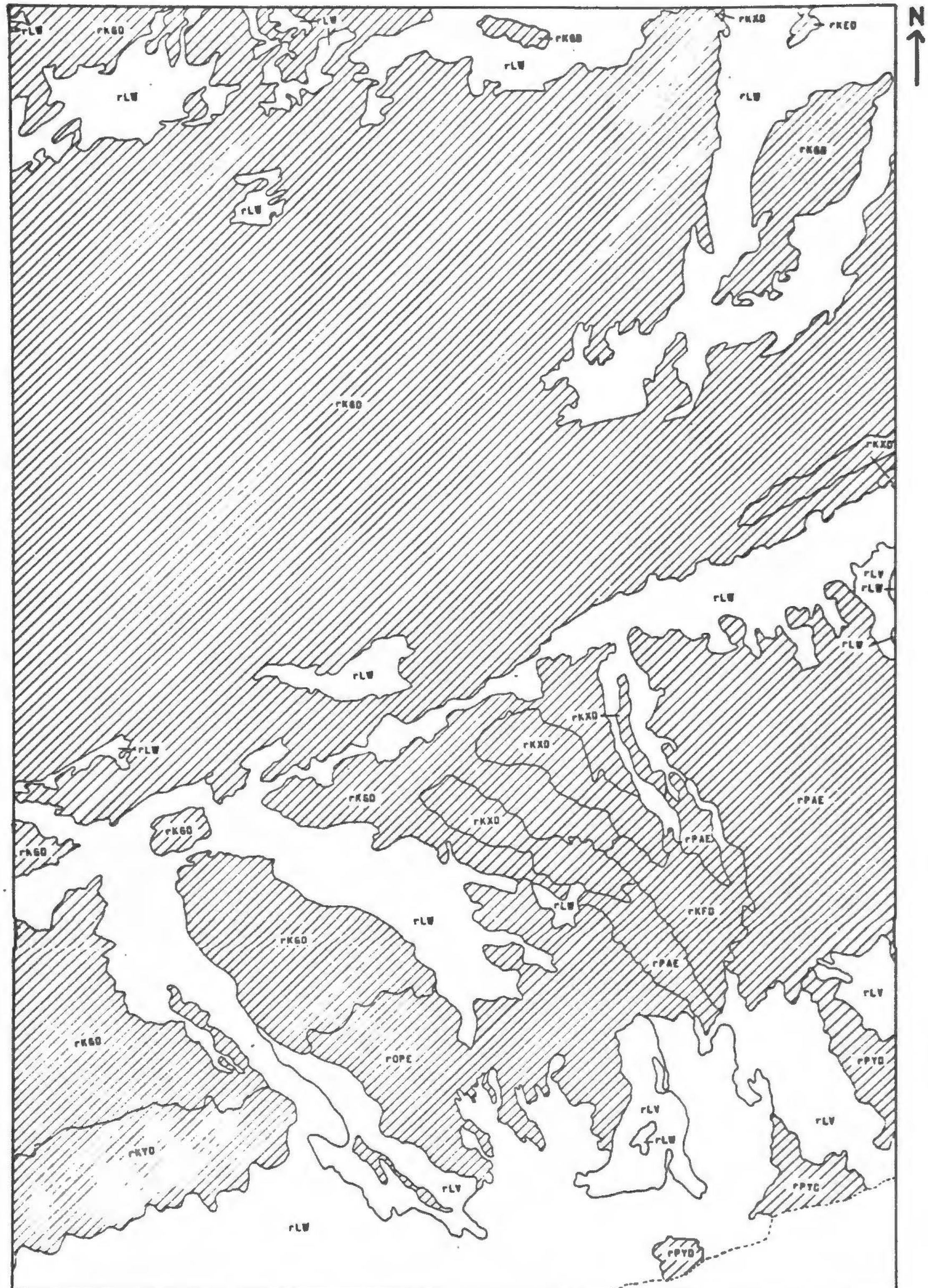

Figure 43. Tropofolists: Quadrangle 23.

Figure 44. Tropofolists: Quadrangle 24.

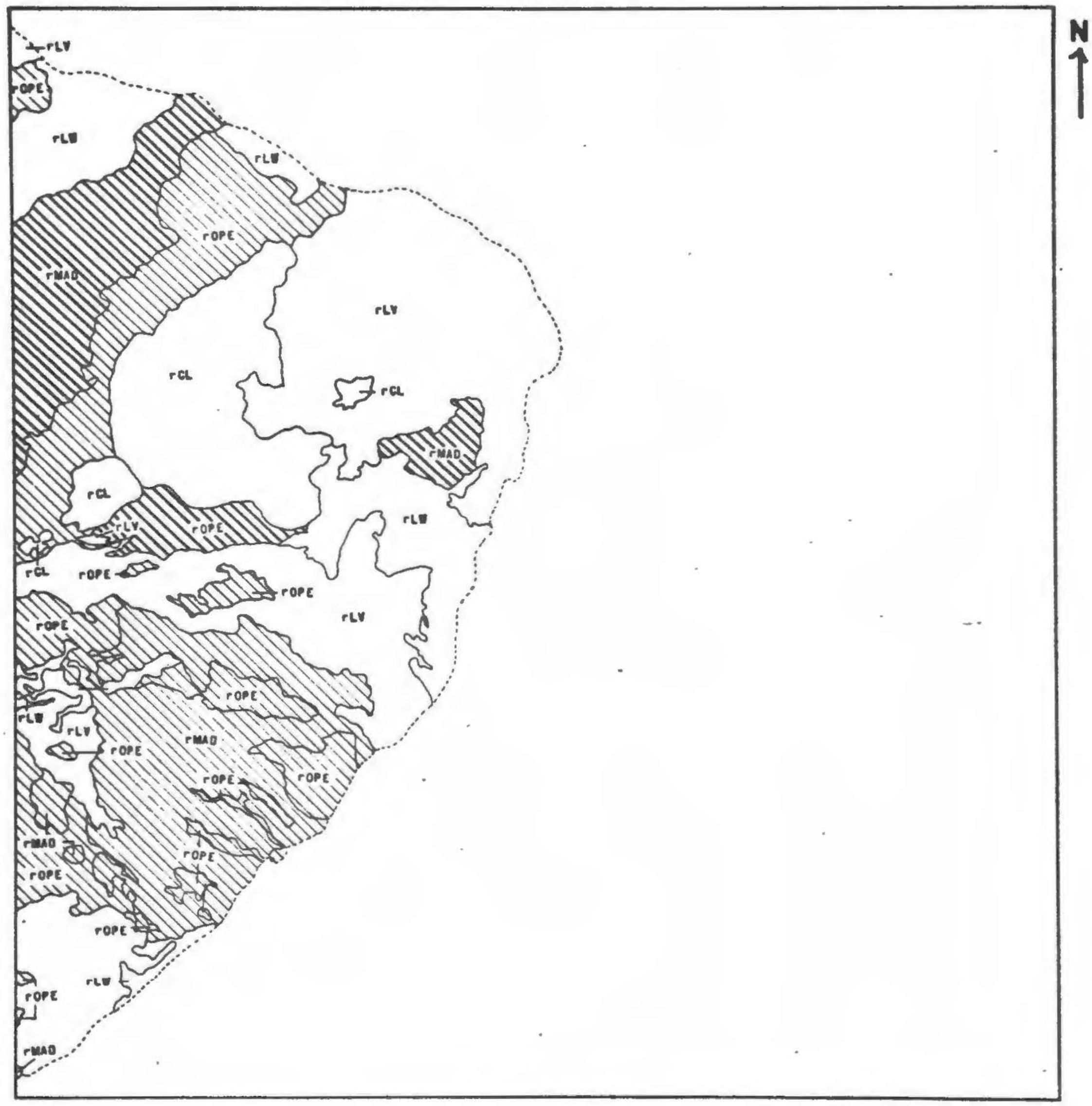

Figure 45. Tropofolists: Quadrangle 25.

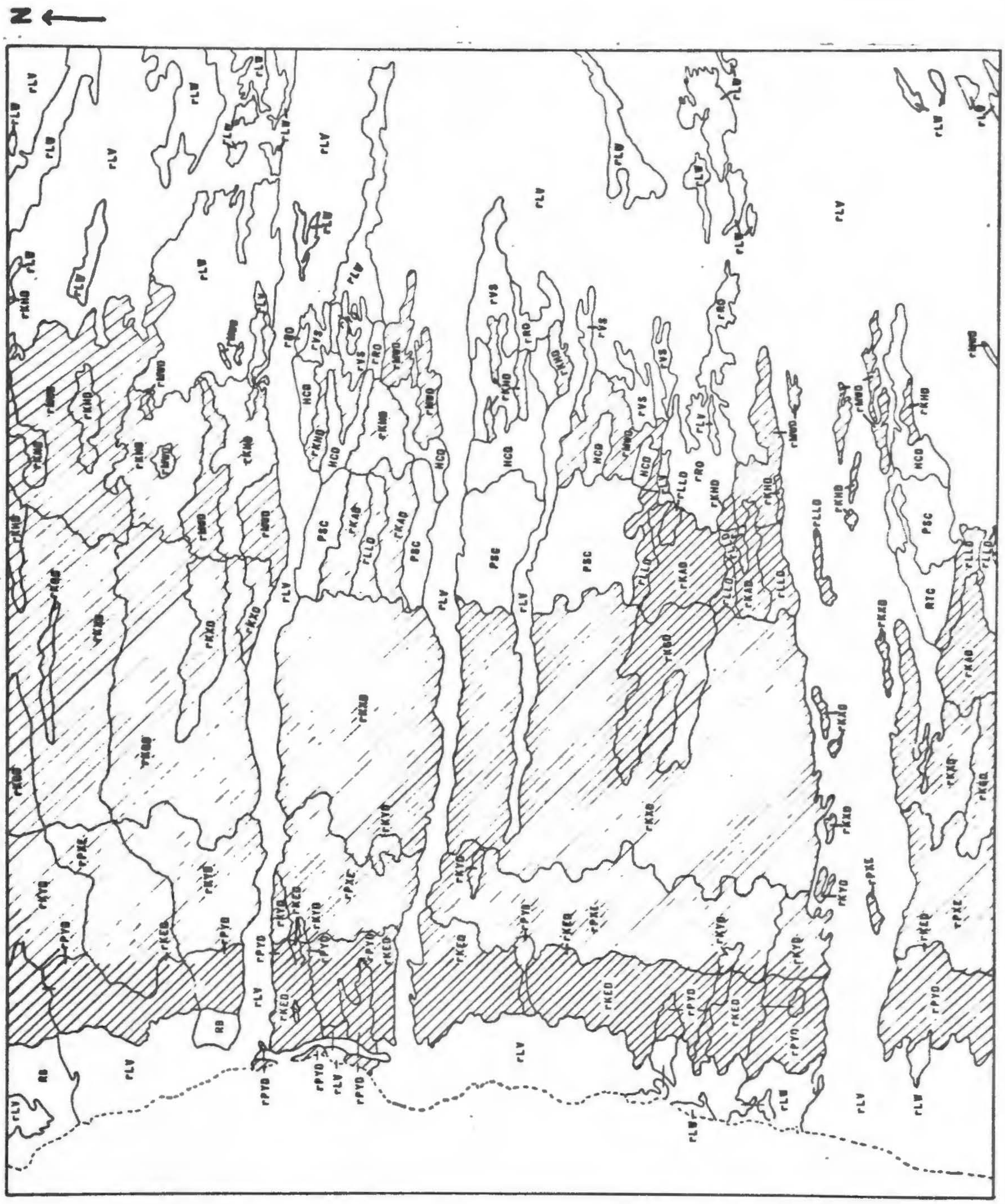

Figure 46. Tropofolists: Quadrangle 26.

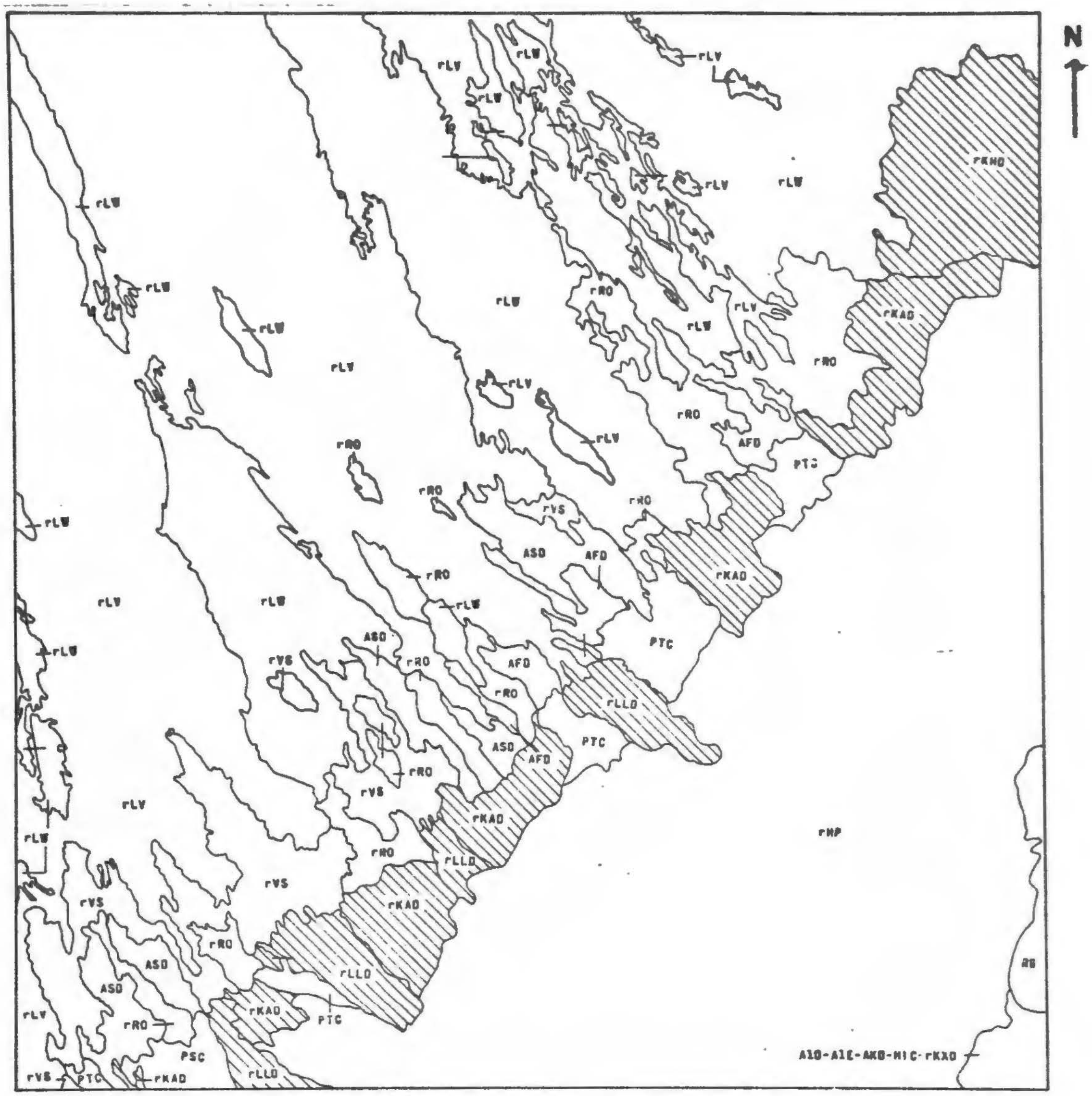

Figure 47. Tropofolists: Quadrangle 27.

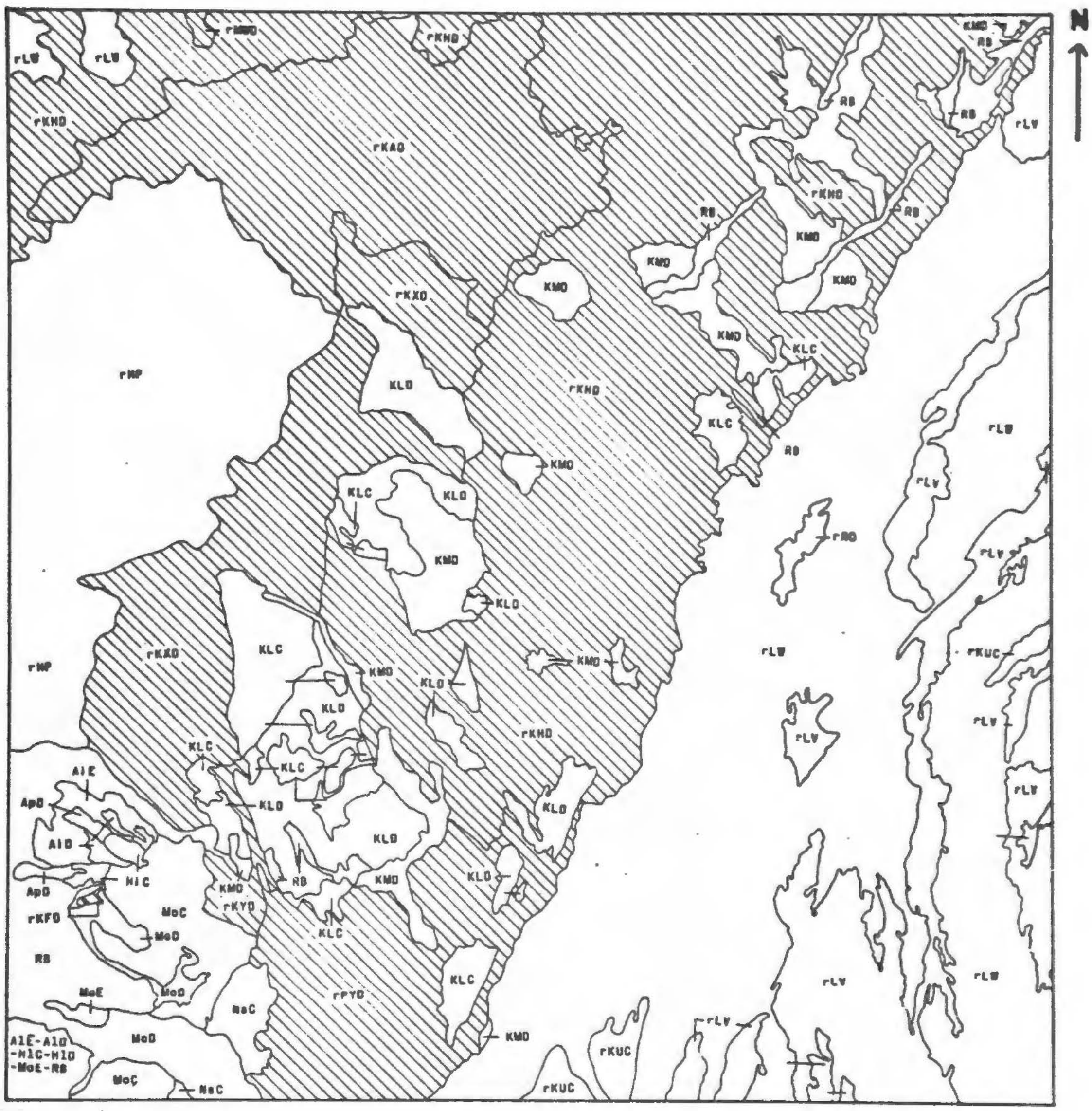

Figure 48. Tropofolists: Quadrangle 28.

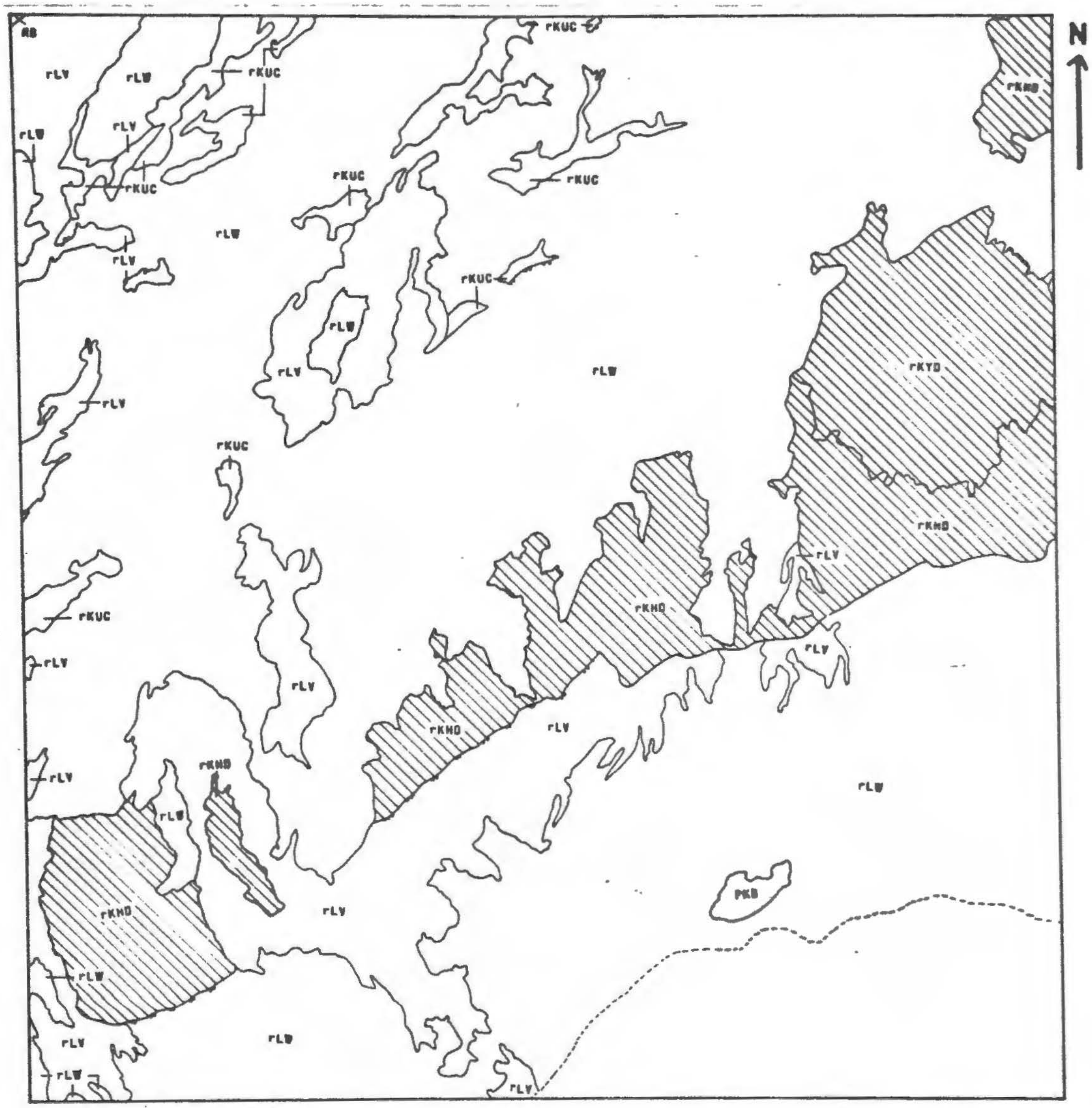

Figure 49. Tropofolists: Quadrangle 29.

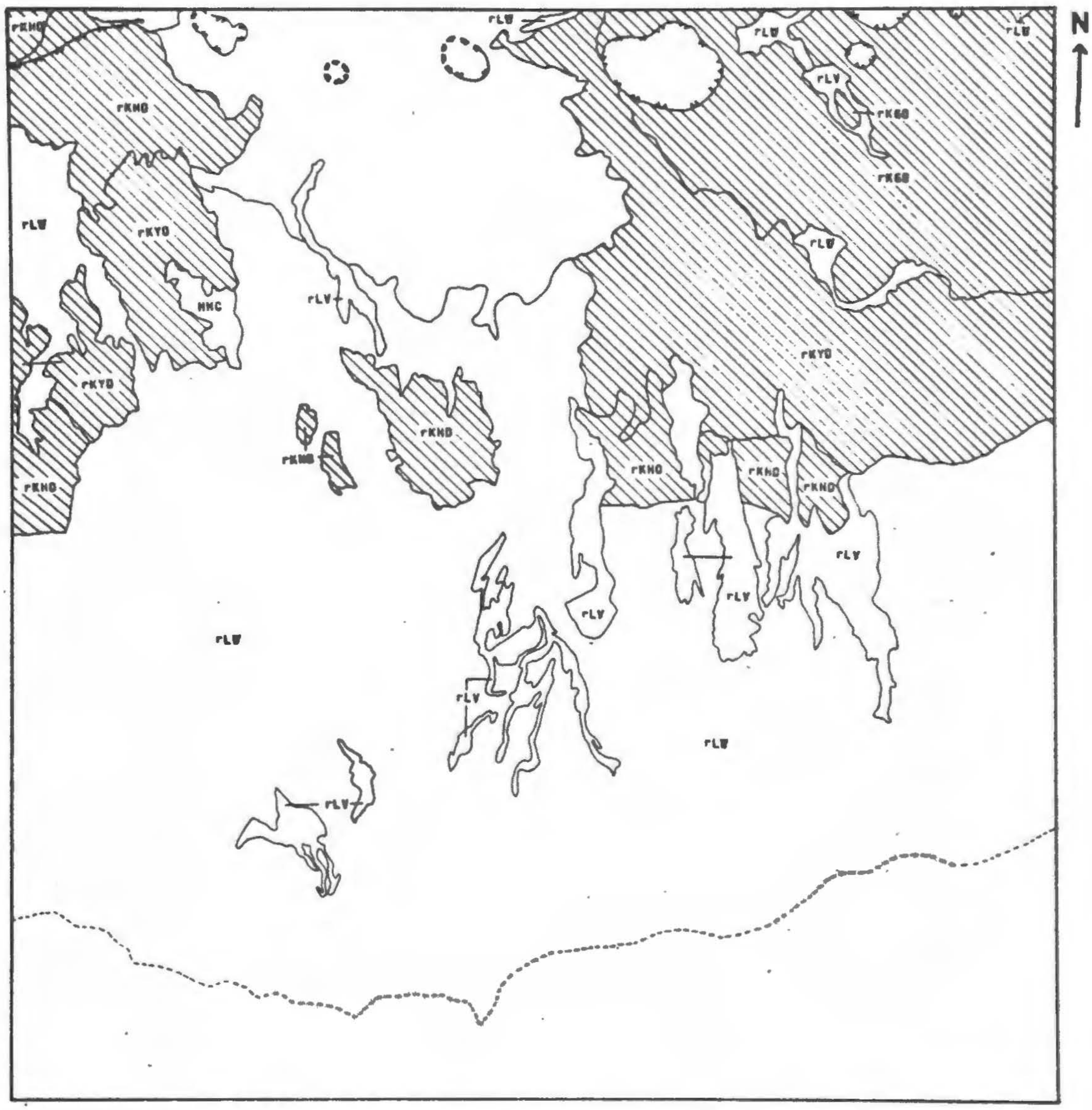

Figure 50. Tropofolists: Quadrangle 30.

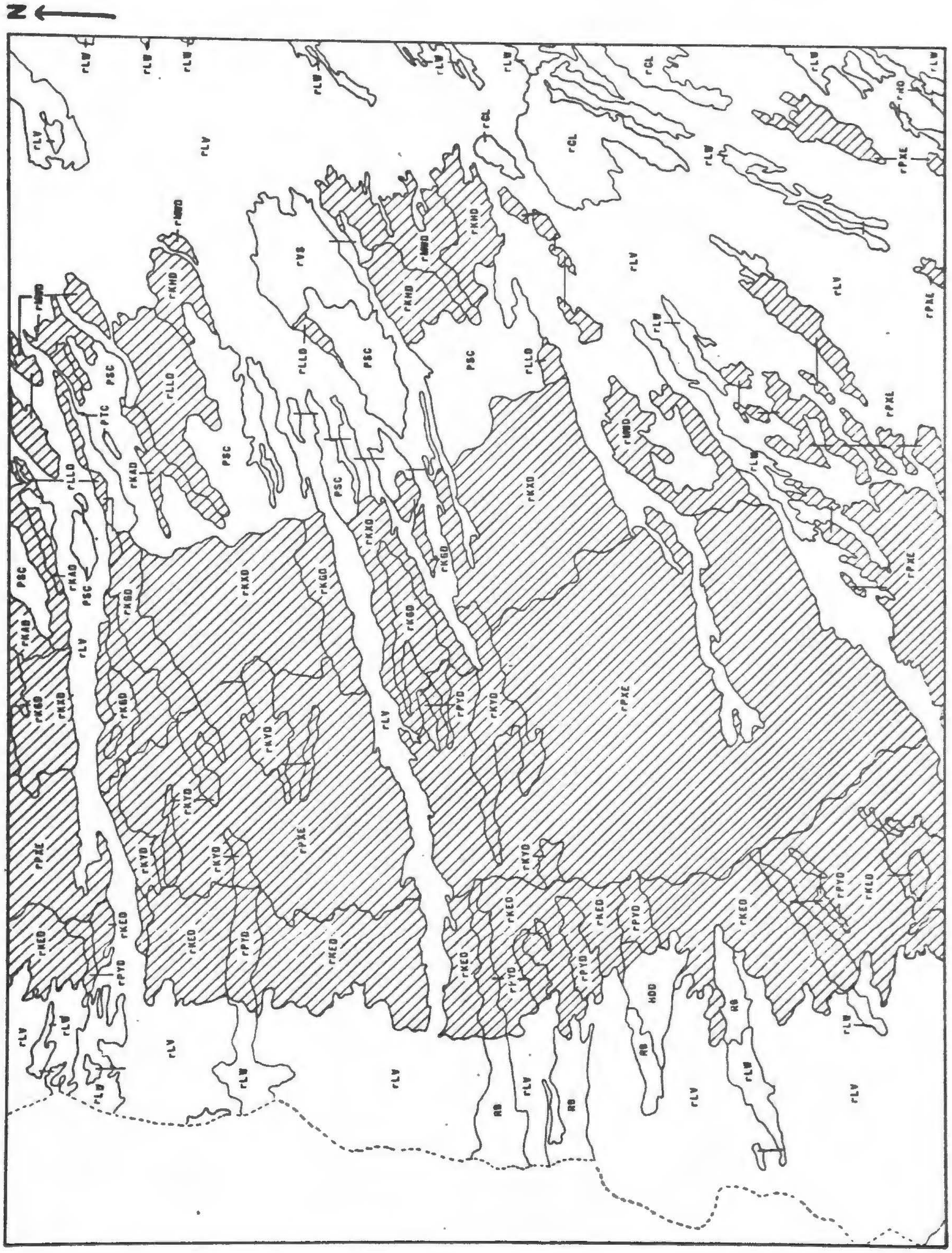

Figure 51. Tropofolists: Quadrangle 31.

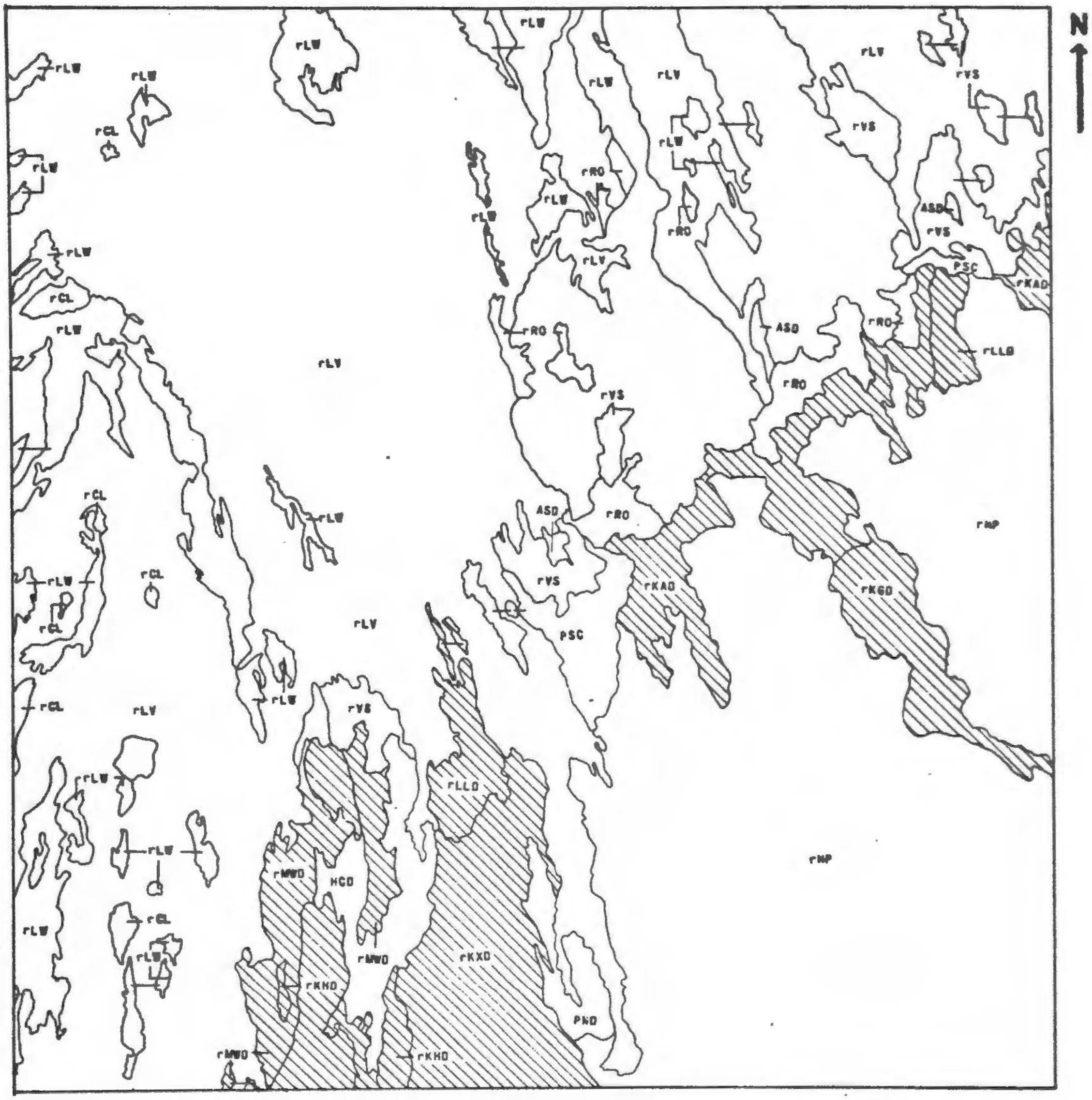

Figure 52. Tropofolists: Quadrangle 32.

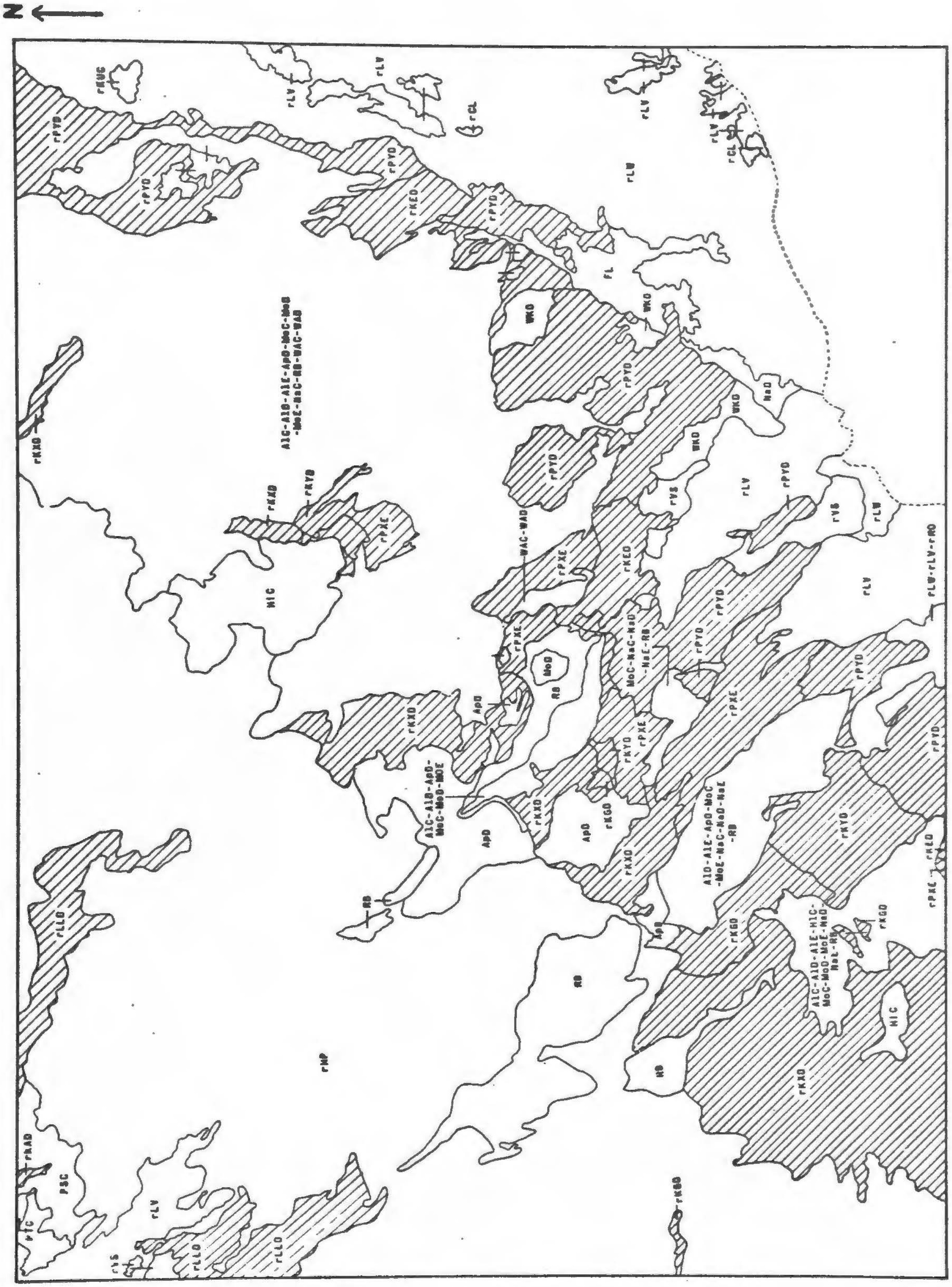

Figure 53. Tropofolists: Quadrangle 33.

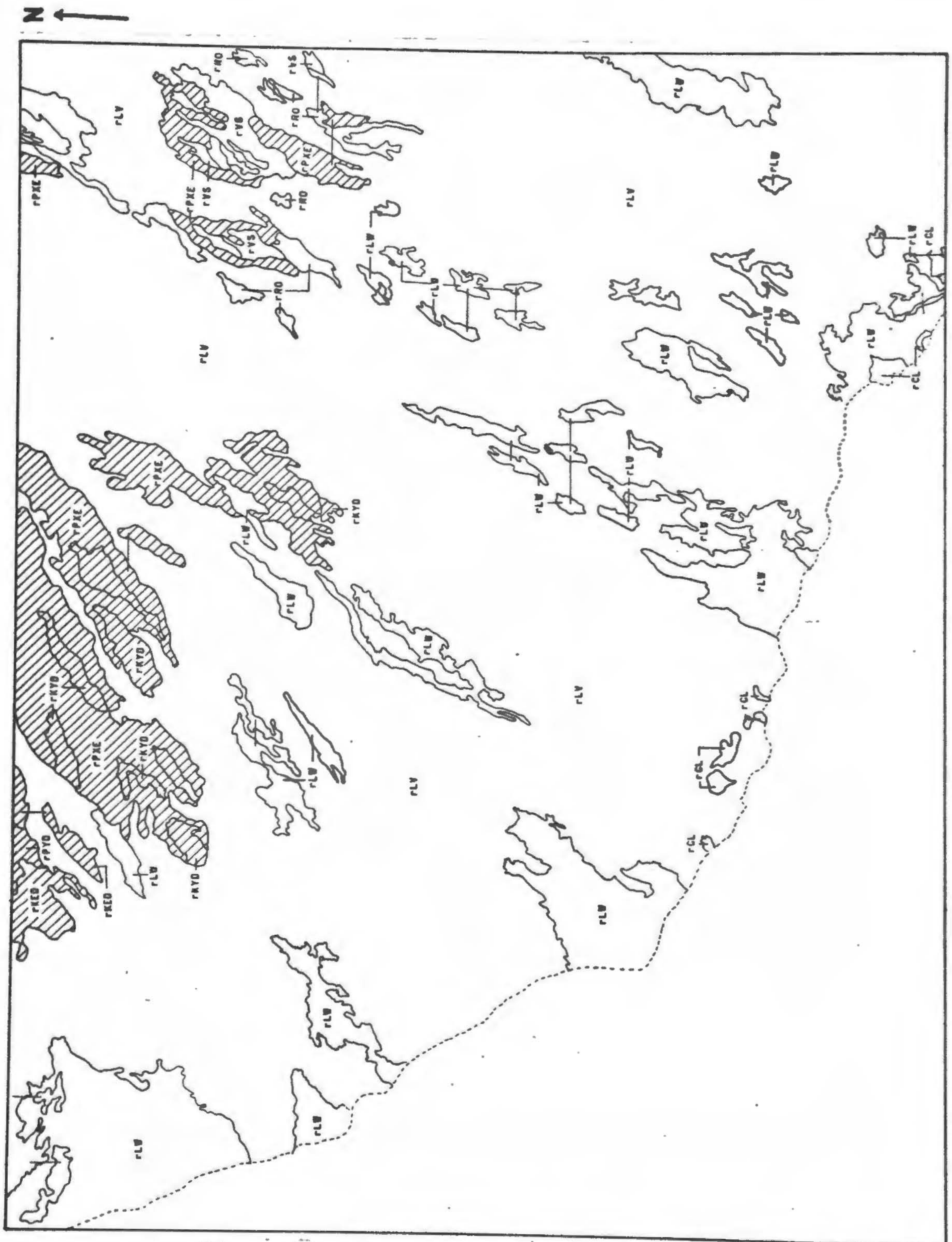

Figure 54. Tropofolists: Quadrangle 34.

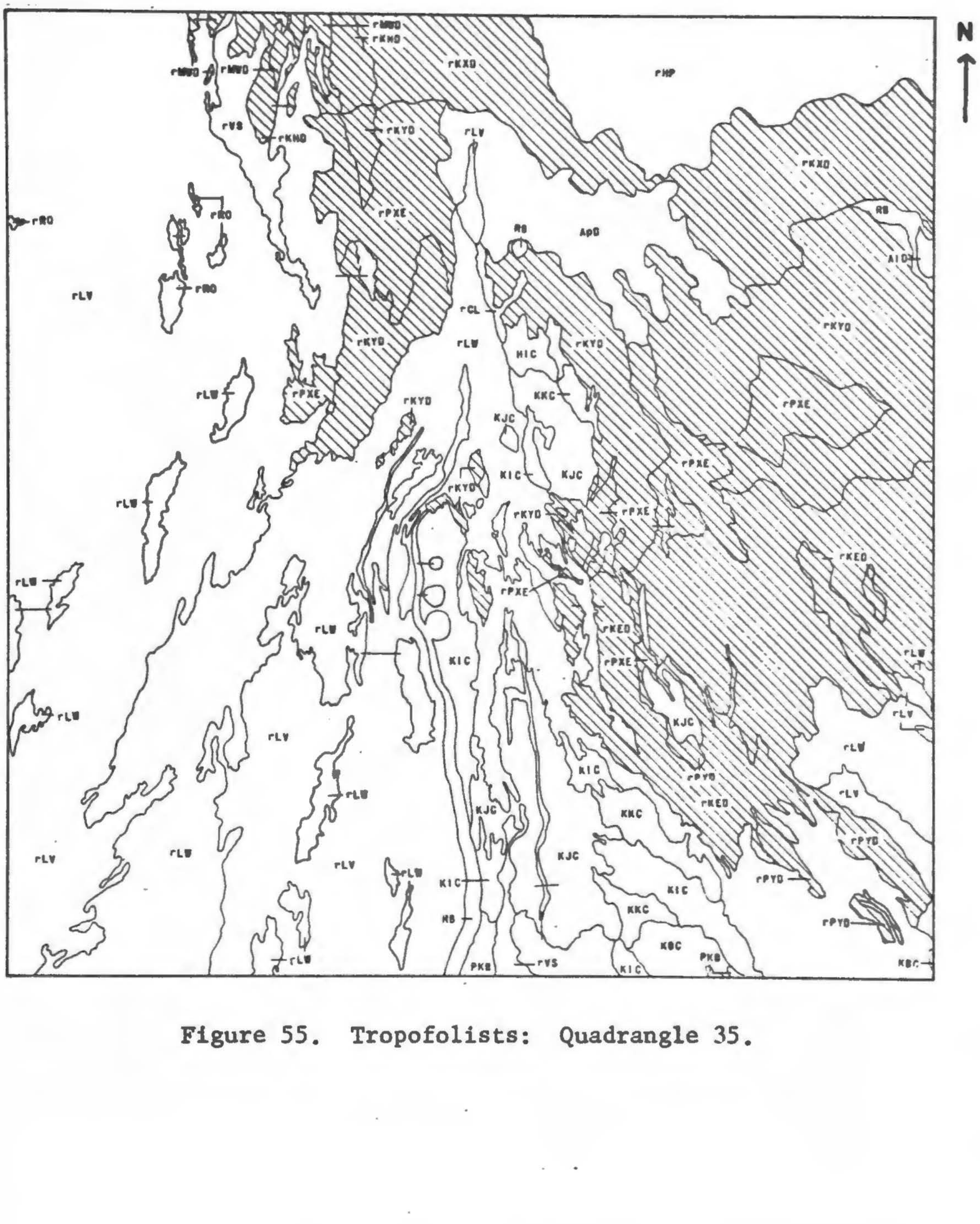

Figure 55. Tropofolists: Quadrangle 35.

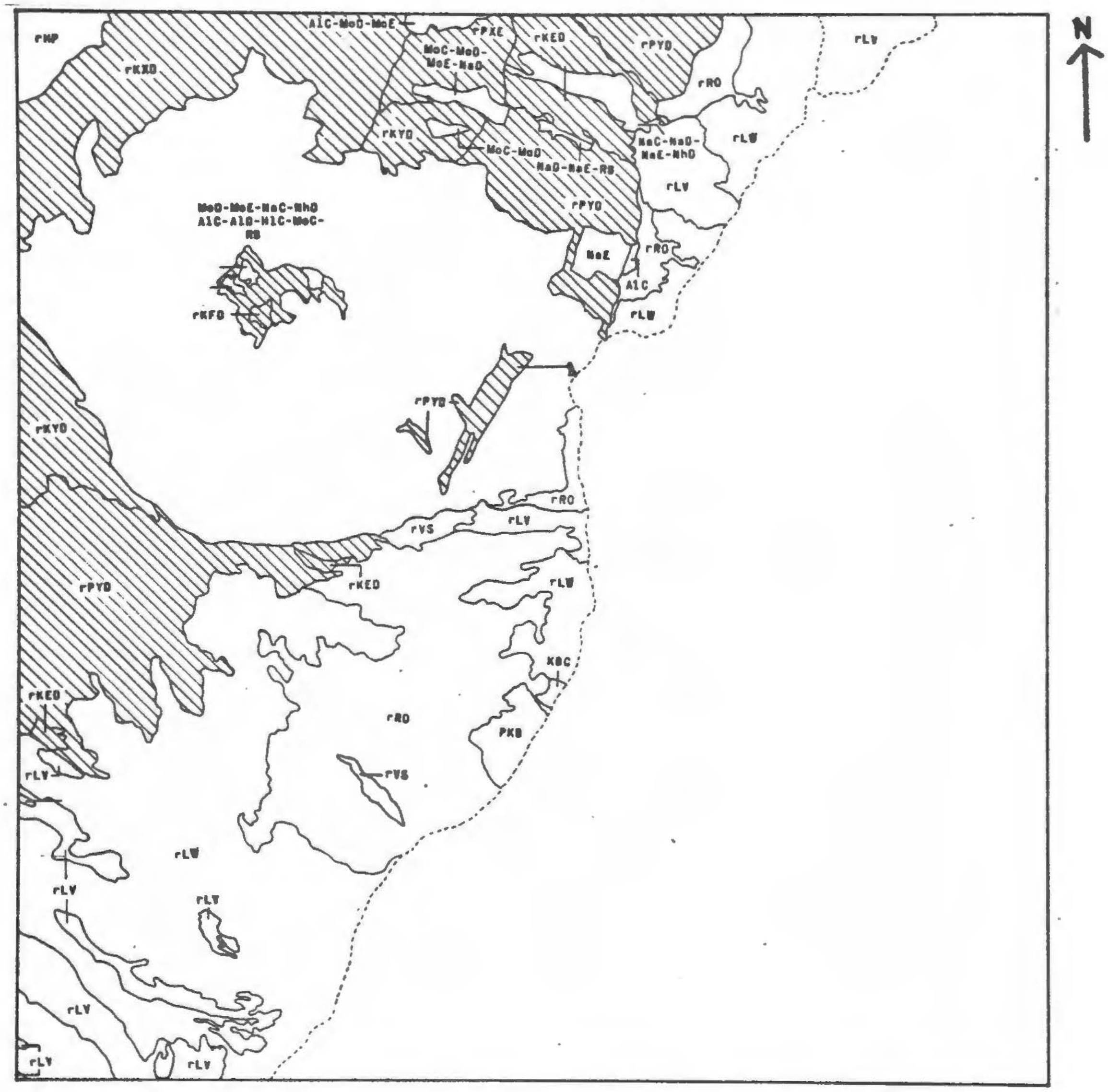

Figure 56. Tropofolists: Quadrangle 36.

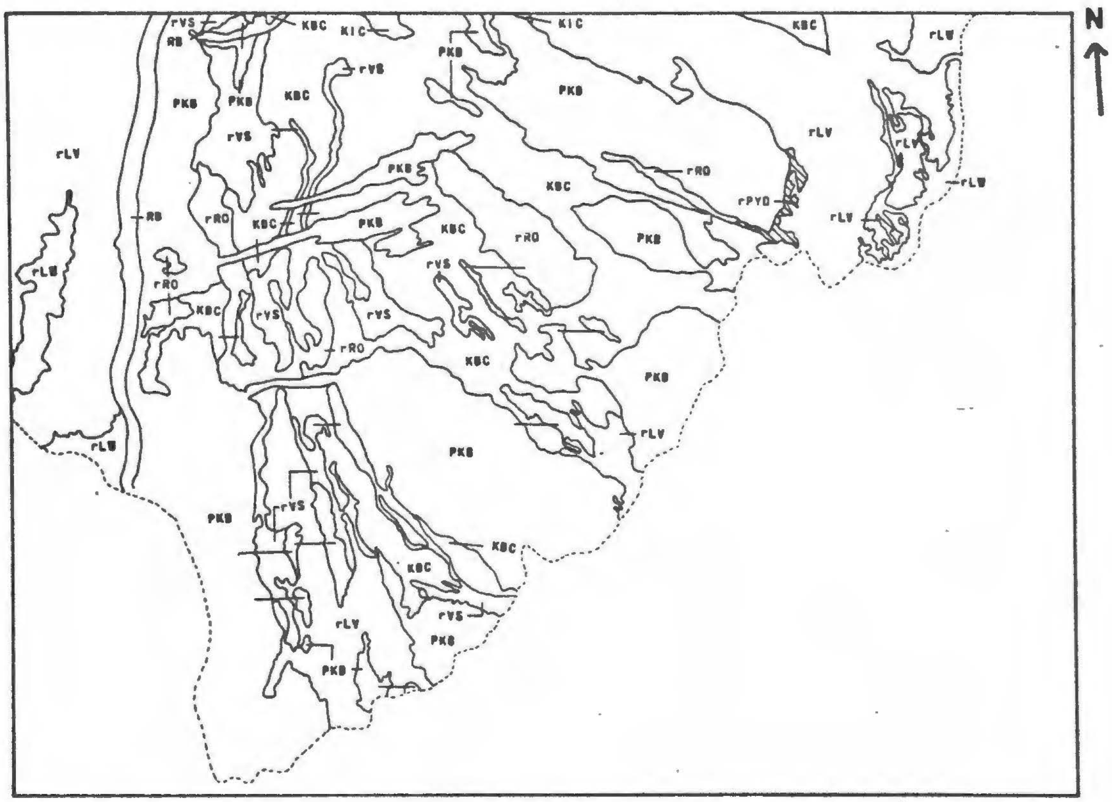

Figure 57. Tropofolists: Quadrangle 37.

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